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Assessment of Risk to Boeing Commercial Transport Aircraft From Carbon Fibers

C.A. Clarke and E.L. Brown

Boeing Commercial Airplane Company
Seattle, Washington

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SYMBOLS AND ABBREVIATIONS

C	Centigrade
CF	Carbon Fibers
CF/m^3	Carbon Fibers per Cubic Meter-density
$CF\ sec/m^3$	Carbon Fiber Seconds per Cubic Meter - exposure
DMC	Direct Maintenance Cost (in 1978 dollars)
E	Exposure - carbon fiber seconds per cubic meter
$\bar{E}$	Mean Exposure to Failure
E_F	Exposure Factor
E_{FA}	Exposure Factor - Avionics Bay
E_{FD}	Exposure Factor - Flight Deck
Fs/m^3	Carbon Fiber Seconds per Cubic Meter-exposure
G	Transfer Function - carbon fiber output to input ratio
in	inch
kg/min	Kilograms per minute
lbs/min	Pounds per minute
mm	Millimeter
Pr(E)	Probability of Exposure
$Pr(UR_{CF})$	Probability of Unscheduled Removal because of Carbon Fibers
T_F	Transfer Function - carbon fiber output to input ratio

ASSESSMENT OF RISK TO BOEING COMMERCIAL TRANSPORT AIRCRAFT FROM CARBON FIBERS

C. A. Clarke, E. L. Brown

Boeing Commercial Airplane Company

1.0 SUMMARY

The conclusions of the assessment are that electronic equipment annual repair costs due to carbon fiber exposure are insignificant and flight safety is not compromised by the effects of carbon fibers. It is recommended that new applications of graphite/epoxy not be inhibited because of concern for carbon fiber ingestion in aircraft.

When the Boeing 707, 727, 737 or 747 aircraft doors are closed and air conditioning is derived from the main engines, carbon fibers do not enter the flight deck or avionics bay. The fibers are broken up and filtered out by the engines, air cleaners, and water separators. The systems are designed to be self cleaning.

If the passenger door galley door, or avionics bay door is open, then the possibility of free carbon fibers entering an aircraft, reaching electronic equipment, and causing a malfunction may arise, expecially when the aircraft is powered from ground power. After factoring in the Bionetics Corporation data, however which shows that malfunction of the electronic equipment requires very high levels of carbon fiber exposure, and especially. the A. D. Little, Inc. data which shows that an aircraft will experience an extremely low probability of carbon fiber exposure, the result is an insignificant annual "expected dollar loss" of from one to four dollars/year/aircraft for removal and cleaning of electronic equipment in the 707, 727, 737, 747 aircraft. The expected dollar loss is for one aircraft at an air terminal. The expected dollar loss is based on United States rate of 3.2 fire accidents per year derived from Boeing, Lockheed, Douglas, and Federal Aviation Administration records.

The annual expected dollar loss for the Boeing Commercial Airplane Company fleet is an insignificant one hundred and forty-five dollars.

2.0 INTRODUCTION

This final report is organized to identify and describe the carbon fiber released from an aircraft fire, carbon fiber characteristics, the number of aircraft that may be exposed at an air terminal, 707/727/737/747 conventional commercial aircraft operating modes at the air terminal, air conditioning air paths and flow rates, CF transfer functions into an aircraft, vulnerable avionic equipment, probabilities of removal, removal costs, and safety. The annual removal cost, "expected dollar loss", from a single aircraft exposure to carbon fiber is calculated for various aircraft, aircraft locations, and exposure levels. The sub-task flow diagram for this investigation is shown in Figure 1.

Carbon fiber exposure levels and avionic equipment malfunction probabilities were supplied by NASA. The "airframe manufacturers" - Boeing, Lockheed, and Douglas cooperated extensively in the following tasks (see Figure 1):

(1) survey airline fleet size, aircraft models and operating modes at nine airports
(2) assess carbon fiber transfer functions into the aircraft
(3) catalog vulnerable avionics equipment
(4) develop cost data
(5) evaluate "unscheduled removal rates" and anticipate costs due to carbon fiber exposure (expected dollar loss)

In the body of the report the aircraft operating modes (1) and the transfer functions (2) are combined into a so-called "exposure factor" to improve the handling of the extensive data developed on this program.

This final report also identifies some of the cause and effect relationships and assesses the significant aircraft vulnerability/immunity parameters.

Results of this aircraft risk assessment are based on work conducted by the Boeing Commercial Airplane Company, P.O. Box 3707, Seattle, Washington, 98124 under contract NAS1-15510 with GFRAPO, NASA Langley, Hampton, Virginia.

The GFRAPO Systems-Vulnerability Manager was Jerry Humble. The Boeing Program Manager was J. C. McMillan. Deputy Program Manager, S. D. Schneider. Task 2, Principal Investigator, C. A. Clarke.

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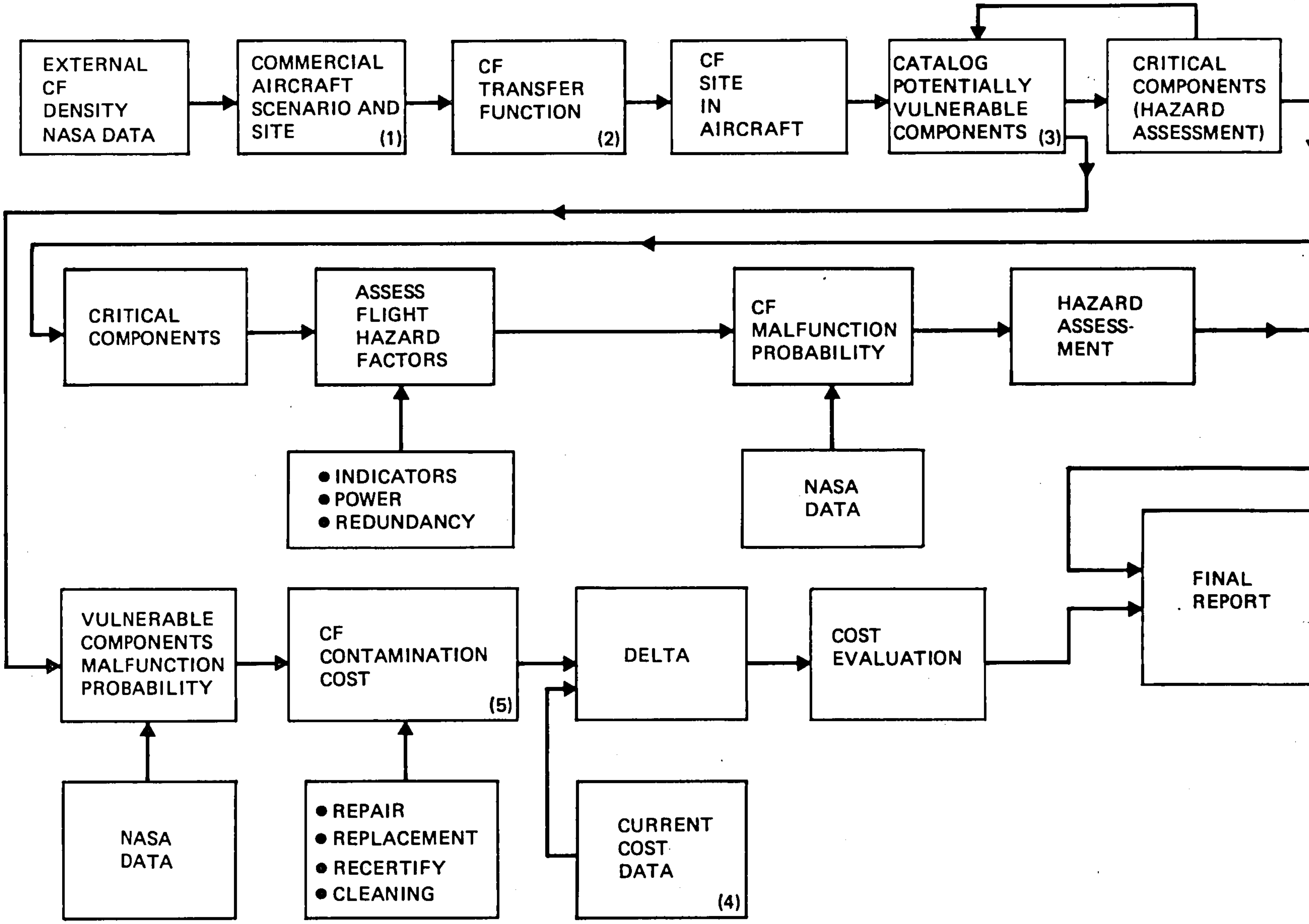

Figure 1.—Carbon Fiber Study

3.0 CARBON FIBER

3.1 CARBON FIBER FROM AN AIRCRAFT FIRE

The potential source of carbon fiber is from a postulated aircraft accident scenario that occurs on or near an airport. Carbon fibers may be released when parts containing carbon fibers burn and under suitable weather conditions fibers are carried to other aircraft operating on the ground at the air terminal. Carbon fibers do not originate from structurally sound graphite/epoxy parts within an aircraft.

Previous studies in the CF risk analysis program determined, in detail, historical fire damage to commercial aircraft and also projected the future use of graphite/epoxy in commercial aircraft up to the year 1993. The fire damage, type of fire, weather conditions, and number of exposed aircraft (1993) have been established in a computer model to simulate a graphite/epoxy aircraft accident at an air terminal. This computer simulation run output provides to this study the amount of carbon fiber released per graphite/epoxy aircraft fire accident, i.e.:

Exposure level (E)
for example, 10^7 CF sec/m^3

at an exposed aircraft at an air terminal and the statistical probability of that level occurring i.e.:

Pr (E)
for example 0.0004

and also the accident rate, for example 3.2 fire accidents per year. The results and conclusions of this aircraft risk study are dependent upon these exposure levels and probabilities.

3.2 CF CHARACTERISTICS

Graphite/epoxy is a layered construction of graphite strands or matting with an epoxy filler formed to make structural panels or parts. In a graphite/epoxy fire, the epoxy melts at 300 to 400°C and CF is released (around 1%) or burned at 600 to 800°C. Single fibers (most less than 5 to 6 millimeters), lint, and fragments are released. Heavy soot accompanies the fire, but it's reported one can see (in the laboratory) a carbon fiber density of 10^5 CF/m^3 in the air and an "exposure" level (E) of 10^6 or 10^7 CF seconds/m^3 deposited on a surface (Reference 3).

In the air, single fibers from a graphite/epoxy fire fall at 3 centimeters per second, lint at 20 centimeters per second, fragments at 150 centimeters per second. Tests indicate that carbon fibers are broken up to harmless lengths of less than one millimeter when ingested in an aircraft engine or compressor (Reference 1). If carbon fibers are assumed to enter an aircraft, lengths of from one to five millimeters may enter avionics equipment through the three millimeter (1/8 inch) diameter cooling holes punched in the housing and cause malfunction. The resistance of the fibers is two to six thousand ohms per centimeter; they burn at 20 to 30 milliamps and above 100 volts. Carbon resistivity is 1.7×10^{-3} ohm centimeters and, for comparison, aluminum resistivity is 3 to 5×10^{-6} ohm centimeters.

Tests within the NASA carbon fiber chamber have simulated extremely heavy exposure levels of 10^7 or 10^8 CF sec/m^3 by cutting carbon fibers to length and inducting and diffusing them into a lab chamber onto aircraft avionic equipment. These levels have caused avionic equipment to malfunction, but no burnout or damage occurred. At these levels the equipment is literally covered with black matted carbon fibers - easily visible. Operation returns to normal after vacuuming (Reference 3).

The average exposure level (E) at which avionic equipment malfunctions is defined as:

Mean Exposure ("$\bar{E}$", "E bar")

for example, 1.5×10^7 CF sec/m^3.

The results and conclusions of this aircraft risk study are dependent upon the "mean exposure" ($\bar{E}$).

A graphite/epoxy fire will create a certain density or concentration (CF/m^3) of carbon fibers in the air which may be deposited on an exposed aircraft. This density (CF/m^3) multiplied by the period of time in seconds (CF sec/m^3) an aircraft or piece of equipment is exposed is defined as Exposure (E).

4.0 CF TO EXPOSED AIRCRAFT

4.1 NUMBER OF AIRCRAFT

If a graphite/epoxy fire occurs near an air terminal, carbon fibers may be deposited on one or a number of exposed aircraft parked at the terminal.

The next two sections will describe the identification of average number of aircraft located at an air terminal, their operating modes when susceptible, length of time in those modes, and carbon fiber paths and transfer functions into the aircraft.

Boeing, Lockheed, and Douglas surveyed and determined the number of airlines and their average fleet size located and operating at nine United States airports. Boeing compiled data from LaGuardia, Logan, and Philadelphia. The airlines were assigned a letter code. The number of aircraft models for each airline and their location at the air terminals during the daytime and nighttime were identified and the airplanes were categorized as "small" or "large" and segregated into groups either at the "gate/ramp" or away from the gate/ramp called "maintenance". See Tables 1, 2 and 3. The large aircraft are 747, DC-10, or L1011. The small are 707, 727, 737, DC-8, DC-9. Medium are DC-9-80, A300. (These categories were made to satisfy the requirement of the risk assessment computer program.)

They are jet aircraft, either passenger or cargo, and are parked on the ground. They are excluded if they are airborne, out-of-service, or propellar driven. Note in the tables that, on the average, during the day there are very few aircraft away from the gate (maintenance) at LaGuardia, Logan, and Philadelphia but, on the average, there are a number of planes parked at the gate during the night. These aircraft are undergoing cleaning and minor maintenance operations for an average period of about four or five hours and they are closed the rest of the night.

The Boeing data in Tables 1, 2, and 3, the Lockheed survey data, and the Douglas survey data were all summarized in Table 4 and submitted by Douglas to NASA and the risk analysis contractors for inclusion in the risk assessment computer model. Thus, Table 4 presents a statistical sample of the average number of aircraft that are exposed - open - to carbon fiber and parked around the air terminals of nine major United States airports in the summer of 1979. The totals of Table 4 are reduced and do not correlate with the relevant totals of Tables 1, 2, and 3 to compensate for aircraft that are closed up after cleaning and minor maintenance during a portion of the night. Aircraft must be operating with electrical power on and doors open to be vulnerable to CF.

Table 1.—LaGuardia International Airport
Average Number of Aircraft

Airline Letter Code	Day Maintenance	Night Gate/Ramp	Night Maintenance	Model
A3	0	1	0	1-DC9
A4	0.1	4	9	13-727
D	0	2	0	1-727, 1-DC9
E	0	13	2	6-DC9, 7-727 1-A300, 1-L1011
N1	0	2	0	2-727
N2	0	0	2	2-727
P	0	0	1	1-737
R	0	2	0	2-DC9
T	0	5	7	12-727
U	0	3	0	1-727, 1-737, 1-DC10
	0.1 small	30 small 2 large	21 small	

Table 2.—Logan International Airport
Average Number of Aircraft

Airline Letter Code	Day Maintenance	Night Gate/Ramp	Night Maintenance	Model
A1	0	1	0	737 or DC9
A3	0.1	6	3	4-DC9, 3-727, 2-BAC111
A4	0	3	5	3-707, 5-727
B	0	3	0	2-727, 1-747
D	0	8	3	11-727
E	0.1	9	3	6-727, 1-L1011, 5-DC9
N2	0	3	0	2-727, 1-DC10
P	0	1	0	1-737 (weekend)
R	0	1	0	1-DC9
T	2	2	0	1-707, 1-DC9
U	0	3	0	2-727, 1-737
	2.2 small	37 small 3 large	12 small 2 large	

Table 3.—Philadelphia International Airport
Average Number of Aircraft

Airline Letter Code	Day Maintenance	Night Gate/Ramp	Night Maintenance	Model
A2	0	2	0	1-737, 1-DC9
A3	0	2	0	1-727, BAC111
A4	0	2	0	1-727, 1-707
B	0	1	0	1-727
D	0	2	0	2-727
E	0	3	0	3-727
N2	0	1	0	1-727
R	0	1	0	1-DC9
T	0.1	5	0	2-727, 2-707, 1-L1011
U	0.1	6	0	3-727, 1-DC8, 2-DC10
	0.2 small	22 small 3 large	0	

Table 4.—Average Number of Exposed Aircraft Per Airport

Airport	Aircraft Size	Day Gate	Day Maintenance	Night Gate	Night Maintenance
ORD	SMALL	41.4	9.0	17.7	19.0
	MEDIUM	2.8	0	1.4	1.0
	LARGE	9.8	2.0	4.5	5.0
JFK	SMALL	40.7	8.0	8.4	18.0
	MEDIUM	3.8	0	1.6	5.0
	LARGE	10.3	2.0	5.8	8.0
STL	SMALL	17.2	2.0	6.1	4.0
	MEDIUM	0.6	0	0.1	0
	LARGE	0.6	0	0.4	0
LGA	SMALL	18.3	0.1	13.2	20.0
	MEDIUM	0	0	0	1.0
	LARGE	0.8	0	1.1	0
BOS	SMALL	14.9	2.2	16.7	13.0
	MEDIUM	0.9	0	0.3	0
	LARGE	2.3	0	1.3	1.0
PHL	SMALL	8.3	0.2	9.6	0
	MEDIUM	0.5	0	0.1	0
	LARGE	1.5	0	1.9	0
DCA	SMALL	16.1	0	9.7	0
ATL	SMALL	30.7	10.0	25.5	16.0
	MEDIUM	2.5	1.0	1.7	1.0
	LARGE	4.1	2.0	3.9	3.0
MIA	SMALL	19.0	4.0	29.7	8.0
	MEDIUM	2.6	0	3.3	2.0
	LARGE	5.9	3.0	5.1	6.0

4.2 OPERATING MODE - EXPOSED AIRCRAFT

Aircraft, listed in Table 4, parked at the air terminal, must be in an operating mode with the passenger door, the galley door, or the avionics bay door open to be susceptible to carbon fiber entry into the flight deck or avionics bay where most of the electrical/electronic equipment is installed in equipment racks. The equipment "draw-through" air conditioning system must be on. The following operating modes have been identified.

APU (PASS) - Auxiliary Power Unit is on and passenger door or galley door open. This is the operating mode when the plane is on an enroute stop or turn around. Some airlines clean and vacuum the plane in this configuration, but an airline effort is underway (1979) to minimize the use of the auxiliary power unit to conserve energy.

GND PWR (PASS) - Ground Electrical Power (fixed or mobile) is operating and the passenger door open. This is the usual mode for cleaning or maintenance. With ground power on, the electronic equipment "draw-through" cooling system is on.

GND PWR (AV) - Ground electrical power is on with avionics bay door open. This is a possible mode for maintenance.

ENG (PASS) - Engines are on, passenger door open. This mode is for an engine run up and checkout during maintenance.

It is also necessary to know the percentage of time aircraft are in these susceptible operating modes. Aircraft modes and correlated time periods in hours from surveys at Logan, Philadelphia, and LaGuardia are shown in Table 5. The time periods in hours are summed and averaged, then totaled for all three airports, then converted to operating time in percent. Table 5 is for nighttime operation at the gate; daytime at the gate was also determined. The operating mode periods of time for day and night operation at the gate are summarized in Tables 6 and 7 for the various door configurations. These are the periods (in percent) when an aircraft may be exposed during a twenty four hour day. Aircraft that are closed up, airborne or parked (not vulnerable to CF) are not included here. Table 6 shows, for example, that at night at the gate with the ground electrical power on and with the avionics door closed, the passenger door is open 50% of the airplane cleaning/checkout "operating mode" GND PWR (PASS). This means CF may enter the passenger door and transfer into the aircraft.

Table 6 and 7 are for aircraft "at the gate/ramp". Lockheed determined similar data for aircraft "away from the gate" (maintenance) shown in Table 13 in the next section.

These operating modes uniquely establish the carbon fiber transfer function from outside to inside the aircraft. In other words, a specific transfer function is assigned for each operating mode.

Table 5.—Exposed Aircraft-Boeing Airport Survey
Night Gate

AIR-LINE	LOGAN APU (PASS)	LOGAN GND (PASS)	LOGAN PWR (AV)	LOGAN ENG (PASS)	PHILA APU (PASS)	PHILA GND (PASS)	PHILA PWR (AV)	PHILA ENG (PASS)	LGA APU (PASS)	LGA GND (PASS)	LGA PWR (AV)	LGA ENG (PASS)
A1	Not Available						N/A				N/A	
A2		N/A					N/A				N/A	
A3	1	4	1	0.1	0.5	3	0.5	0.1			N/A	
A4	1	5	2	0	0.5	3	1	0	1	0	4	0.1
B		N/A				2	4	1	0.1		N/A	
D	3	0	6	0.1	0.25	0	3	0	3	0	6	0
E	3	3	1	0.1	0.25	3	0.5	0.5	1	2	1	0.1
N1		N/A					N/A		0.5	4	1	0.25
N2	0.5	4	1	0	2	4	1	0.1	1	2	1	0.1
P	0	3	1	0.1			N/A		1	2	1	0.1
R	0	3	1	0.1	0.25	4	3	0	1	2	1	0.1
T	1	8	0.5	0	2	4	1	0.1	0.5	4	1	0.25
U	0	3	1	0.1	1	5	0.25	0.1	0.5	4	1	0.25
AVG. HR.	1.05	3.66	1.61	0.06	0.97	3.33	1.25	.11	1.05	2.22	1.88	0.14

	APU (PASS)	GROUND POWER (PASS)	GROUND POWER (AV)	ENG. (PASS)
Grand Total Hours	1.02	3.07	1.58	.10 Ave.
Operating Time Percent	17%	53%	27%	1.7% Ave.
Rounded	18%	50%	30%	2%

Table 6.—Exposed Aircraft Percent Time Summary - Night Gate, Avionics Door

	OPEN PASSENGER DOOR		CLOSED PASSENGER DOOR	
	OPEN	CLOSED	OPEN	CLOSED
APU	0	0	18%	0
ENGINE	0	0	2%	0
AIR CART	0	0	0	0
GROUND POWER	30%	0	50%	0
NONE	0	0	0	PARK

Table 7.—Exposed Aircraft Percent Time Summary - Day Gate, Avionics Door

	OPEN PASSENGER DOOR		CLOSED PASSENGER DOOR	
	OPEN	CLOSED	OPEN	CLOSED
APU	1%	0	95%	0
ENGINE	0	0	0	0
AIR CART	0	0	0	0
GROUND POWER	0	0	4%	0
NONE	0	0	0	PARK

5.0 AIRCRAFT CF TRANSFER FUNCTION

Three things are required in the evaluation of carbon fiber transfer from outside to inside the aircraft:

1) Air flow rates into the avionics bay. This information was needed to aid the NASA risk analysis contractors in the CF testing program on avionics equipment and air conditioning equipment.

2) CF transfer functions, outside to inside the aircraft, to reveal possible amount of CF reaching the avionics equipment:

$$\text{Transfer Function } (T_F) = \frac{\text{CF reaching Avionics (E)}}{\text{CF external to Aircraft (E)}}$$

(A transfer function may also be given for a component or a particular section of the aircraft. It is the carbon fiber output divided by the input and is unitless).

3) A combining of the transfer function (T_F) and the aircraft operating mode percent time, from Tables 6 and 7, to establish a "factor" which determines the avionic equipment CF exposure, i.e.:

$$T_F \text{ X \%Time} = \text{Exposure Factor } (E_F)$$

The "exposure factor" (E_F) is defined as the transfer function multiplied by the percent time the aircraft is in an operating mode. It will be averaged to include all operating modes occurring when the aircraft is at "day-gate" or "night-gate" or "day/night maintenance". The exposure factor (E_F) is a factor that lowers the "exposure" (E) of internal equipment because of the combined aircraft transfer function (T_F) and limited time in an operating mode.

5.1 AIR FLOW RATES

The Boeing 727-200 air conditioning computer program was run using standard, cold, and hot day temperatures (based on ambient temperatures at nineteen cities) to determine the flow rate of air from the engine bleed, or the auxiliary power unit, through the air cleaners and water separator to the Flight Deck and the Avionics Bay. Air flow rates are shown in Figure 2 for a "standard day" 15°C (59°F) with the auxiliary power unit on.

5.2 CF TRANSFER FUNCTION

Air and carbon fiber paths into the aircraft are through open doors or the pneumatic ground cart. The ground cart is seldom used and CF ingested into the auxiliary power unit or main engine (turbo compressor for the 707) is atomized. Figures 3 through 7 show the paths through the open doors to the flight deck and avionics bay.

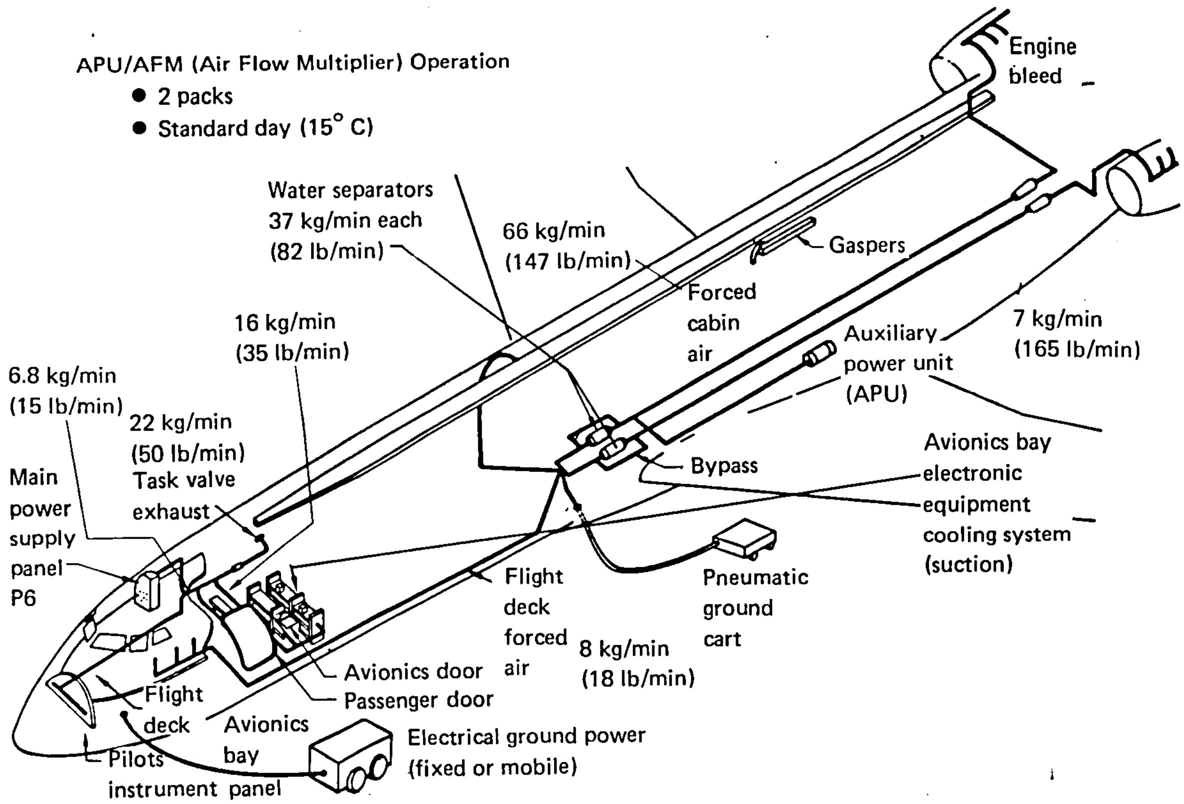

Figure 2.—Air Flow Rates—Auxiliary Power Unit On

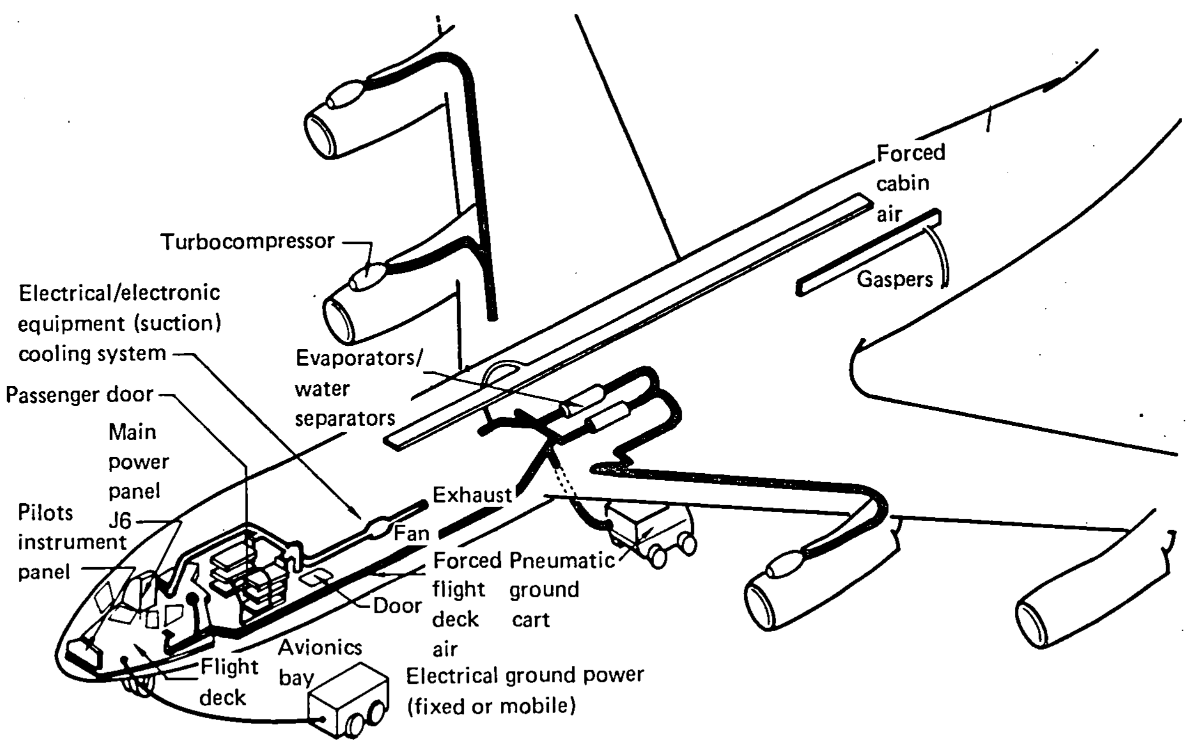

Figure 3.—707 Air/Carbon Fiber Flow Paths

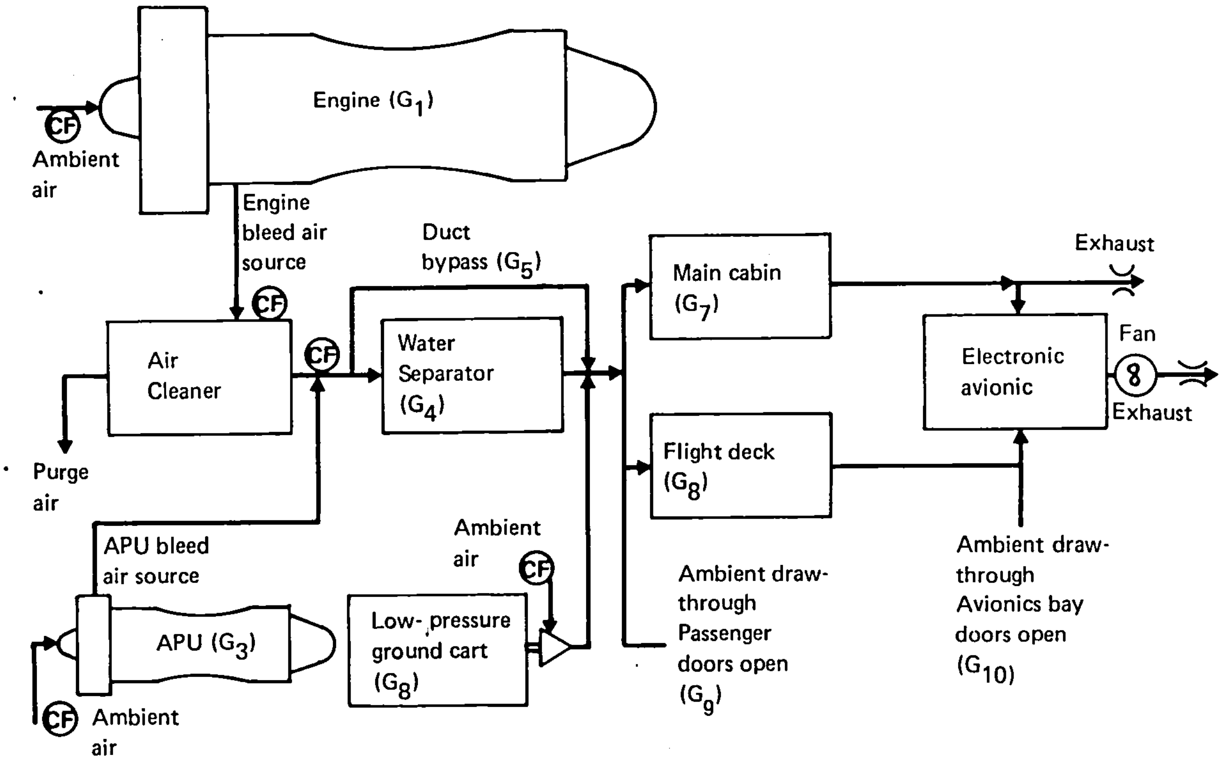

Figure 4.—Typical CF Transfer Paths—727 Airplane

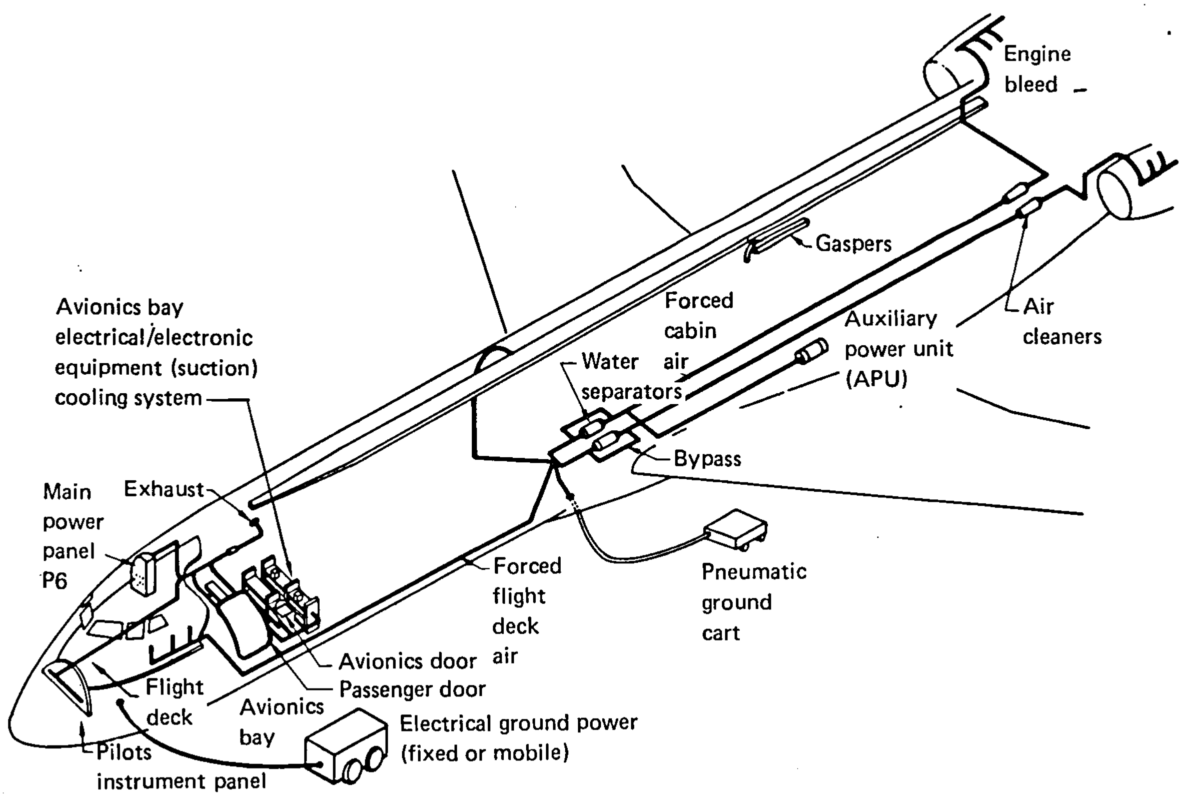

Figure 5.—727 Air/Carbon Fiber Flow Paths

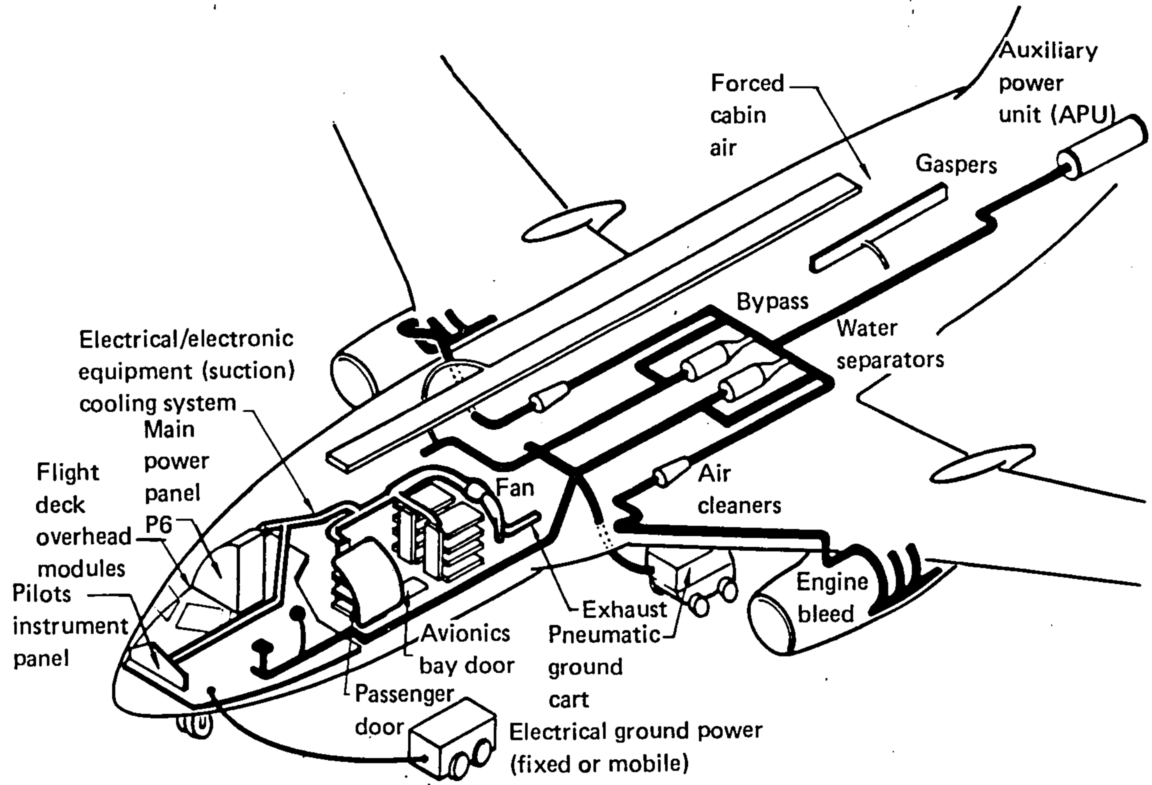

Figure 6.—737 Air/Carbon Fiber Flow Paths

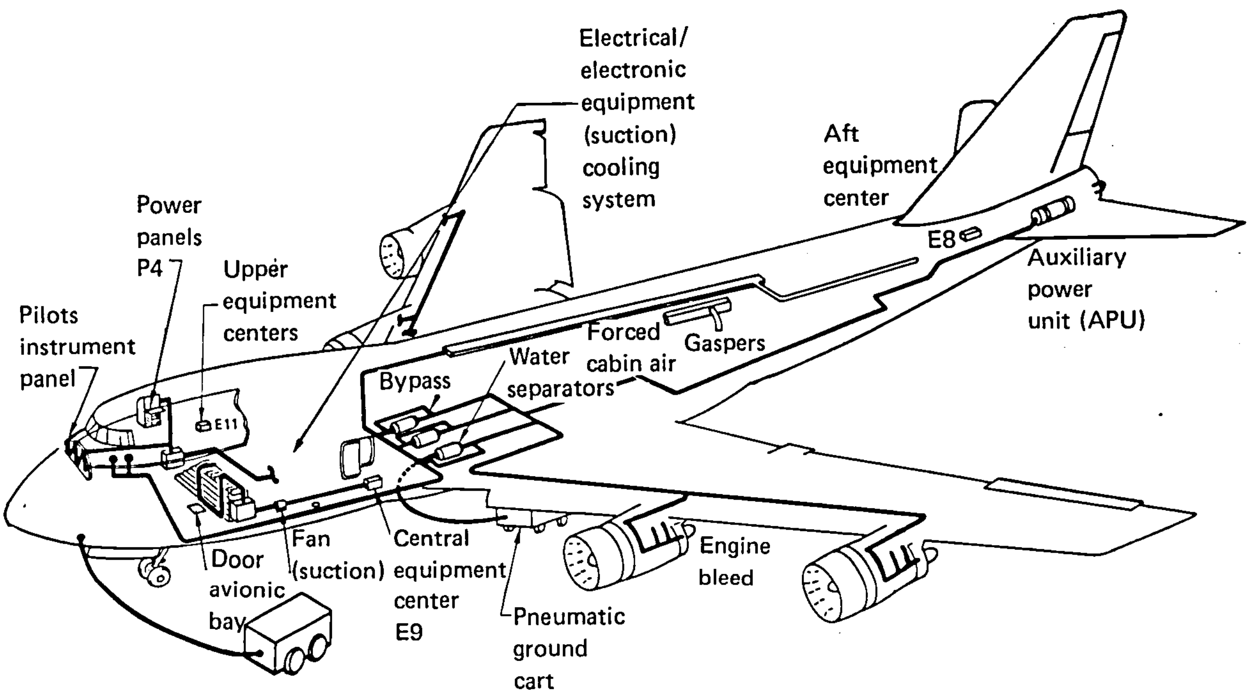

Figure 7.—747 Air/Carbon Fiber Flow Paths

In Figure 5, for example, an entry path may be through the passenger door with the CF being pulled down the sidewalls of the cabin then through the louvers along the base board and down into the avionics bay. The CF is drawn by the avionics bay equipment suction cooling system. Note that conditioning air from the engine bleed is forced into the cabin and flight deck, but cooling air for avionic bay equipment is drawn through and out of the avionics bay by the avionics bay cooling system and exhausted overboard. Avionics equipment is most vulnerable when main engines are off and avionics bay cooling system is on, i.e., when electrical ground power is on - "GND PWR (PASS)" or "GND PWR (AV)".

As the CF moves into the cabin, a certain amount of it will settle out and some will continue through establishing a "transfer function". A transfer function of 0.7 has been selected as a reasonable average for the cabin. Figure 4 shows sections of the aircraft that have been allocated specific transfer functions; the main cabin is G_7, and therefore G_7 equals 0.7.

Table 8 gives each individual transfer function assigned to components and sections of the airplane. NASA's risk analysis contractors measured the transfer function of the air cleaner and the water separator with the resulting data shown in Figures 8 and 9 (Reference 2). These data were rounded off and conservative values selected. Also note that the main engines, turbo- compressor, and APU are shown as having a transfer function of 0.5 whereas recent data has indicated a transfer function of 0.1 or less.

The product of the component and section transfer functions of Table 8 (in accordance with Figure 4 and recognizing the unique CF transfer paths of each aircraft shown in Figure 3, 5, 6, and 7) determine the total transfer function from outside to inside the aircraft. Tables 9 through 12 tabulate these for the various operating modes and door configurations. For example, looking at Table 8 and Table 10 to calculate the transfer function under conditions of engine idle and doors closed on the 727, one would multiply G_1, G_2 (idle), G_4 (low flow), and G_7 or G_8 (which are 0.5, 0.01, 0.001, 0.7) and obtain 3.5×10^{-6} which is rounded to 4×10^{-6}. Some of the transfer functions are not calculated in this manner because of the effects of the air conditioning bypass systems.

Table 8.—Carbon Fiber Transfer Functions

Label	Transfer Function	Value
G_1	MAIN ENGINES/TURBOCOMPRESSOR	0.5
G_2	AIR CLEANER - IDLE	0.01
	- HIGH POWER	0.001
G_3	APU ONLY	0.5
	APU/AFM COMBINATION	0.6
G_4	WATER SEPARATOR - LOW FLOW	0.001
	- APU FLOW	0.005
	- TAKEOFF POWER	0.01
G_5	HEAT EXCHANGERS, DUCTS	1.0
G_6	LOW PRESSURE GROUND CART	1.0
G_7	MAIN CABIN	0.7
G_8	FLIGHT DECK	0.7
G_9	PASS DOOR	1.0
G_{10}	AVIONIC DOOR	1.0

Table 9.—707 Carbon Fiber Transfer Functions

OPERATING MODE	PENETRATIONS		TRANSFER FUNCTION	
	FORWARD PASSENGER DOOR	AVIONICS DOOR	FLIGHT DECK	AVIONICS BAY
ENGINE IDLE	CLOSED	CLOSED	1.2×10^{-2}	1.2×10^{-2}
	CLOSED	OPEN	1.2×10^{-2}	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0
TAKEOFF POWER	CLOSED	CLOSED	4×10^{-3}	4×10^{-3}
GROUND ELECTRICAL POWER	CLOSED	CLOSED	0.2	0.5
	CLOSED	OPEN	0.5	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0
GROUND ELECTRICAL POWER AND LOW PRESSURE GROUND CART	CLOSED	CLOSED	0.7	0.7
	CLOSED	OPEN	0.7	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0

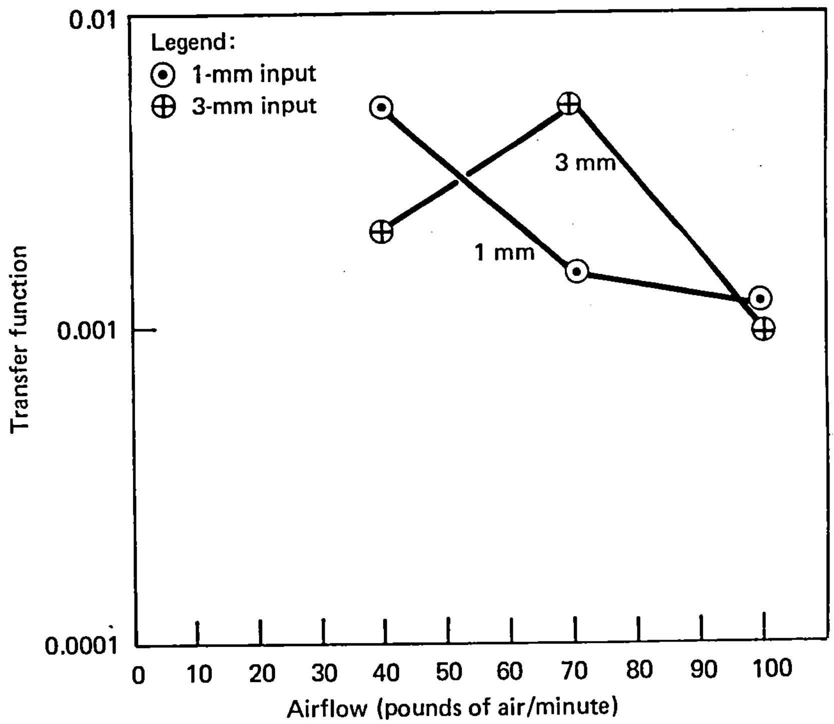

Figure 8.—Air Cleaner T_F

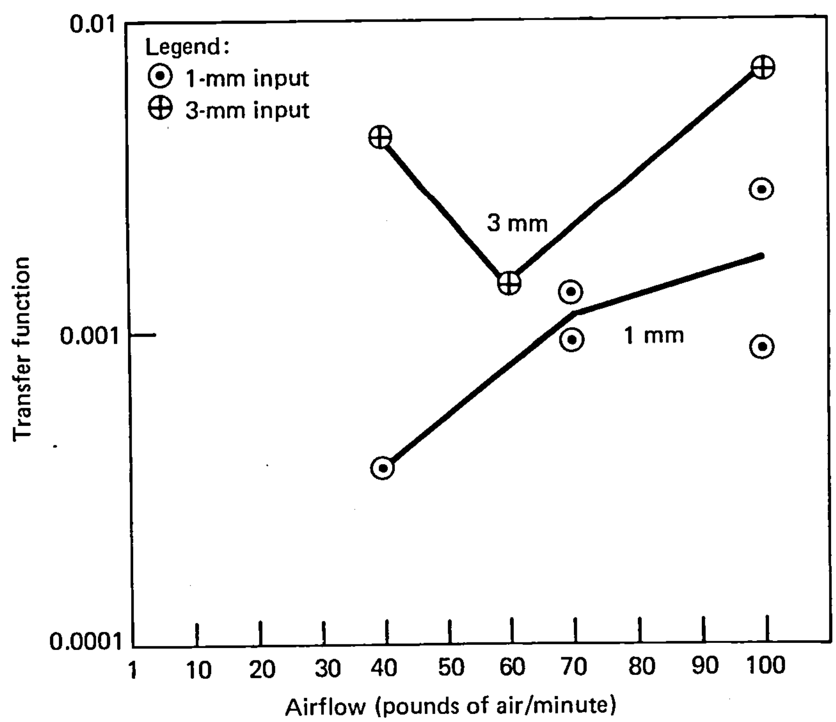

Figure 9.—Water Separator T_F

Table 10.—727 Carbon Fiber Transfer Functions

OPERATING MODE	PENETRATIONS: FORWARD PASSENGER DOOR	PENETRATIONS: AVIONICS DOOR	TRANSFER FUNCTION: FLIGHT DECK	TRANSFER FUNCTION: AVIONICS BAY
ENGINE IDLE	CLOSED	CLOSED	4×10^{-6}	4×10^{-6}
	CLOSED	OPEN	4×10^{-6}	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0
TAKEOFF	CLOSED	CLOSED	4×10^{-6}	4×10^{-6}
APU	CLOSED	CLOSED	2×10^{-3}	2×10^{-3}
	CLOSED	OPEN	2×10^{-3}	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0
GROUND ELECTRICAL POWER	CLOSED*	CLOSED*	0.2	0.2
	CLOSED*	OPEN	0.2	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0

*Air is entering the aft "outflow valve".

Table 11.—737 Carbon Fiber Transfer Functions

OPERATING MODE	PENETRATIONS: FORWARD PASSENGER DOOR	PENETRATIONS: AVIONICS DOOR	TRANSFER FUNCTION: FLIGHT DECK	TRANSFER FUNCTION: AVIONICS BAY
ENGINES IDLE	CLOSED	CLOSED	4×10^{-6}	4×10^{-6}
	CLOSED	OPEN	4×10^{-6}	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0
TAKEOFF POWER	CLOSED	CLOSED	3.2×10^{-5}	3.2×10^{-5}
APU	CLOSED	CLOSED	2×10^{-3}	2×10^{-3}
	CLOSED	OPEN	2×10^{-3}	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0
GROUND ELECTRICAL POWER	CLOSED*	CLOSED*	0.2	0.2
	CLOSED*	OPEN	0.2	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0

* Air is entering the aft "outflow valve".

Table 12.—747 Carbon Fiber Transfer Functions

OPERATING MODE	PENETRATIONS FORWARD PASSENGER DOOR	PENETRATIONS AVIONICS DOOR	TRANSFER FUNCTION FLIGHT DECK	TRANSFER FUNCTION AVIONICS BAY
ENGINES IDLE	CLOSED	CLOSED	10^{-4}	10^{-4}
	CLOSED	OPEN	10^{-4}	10^{-4}
	OPEN	CLOSED	10^{-4}	10^{-4}
	OPEN	OPEN	10^{-4}	10^{-4}
TAKEOFF POWER	CLOSED	CLOSED	10^{-4}	10^{-4}
APU	CLOSED	CLOSED	10^{-4}	10^{-4}
	CLOSED	OPEN	10^{-4}	10^{-4}
	OPEN	CLOSED	10^{-4}	10^{-4}
	OPEN	OPEN	10^{-4}	10^{-4}
GROUND ELECTRICAL POWER	CLOSED*	CLOSED*	0.2	0.2
	CLOSED*	OPEN	0.2	1.0
	OPEN	CLOSED	0.7	0.7
	OPEN	OPEN	0.7	1.0

* Air is entering the aft "outflow valve".

These transfer functions for these operating modes and door configurations will be combined with the average "percent time" in each mode to arrive at the exposure factor, but these facts should be noted first, viz.:

1) The transfer function values of 0.2 and 0.5 have been set at 0.7 and the very low values of 10^{-2} for the 707 and 10^{-3} or less for the 727/737 have been ignored to simplify calculations in the following sections.

2) The flight deck door is assumed open. If closed, CF will not enter there from the passenger door.

3) The 747 operating with engines on or APU on has a positive pressure in the cabin which inhibits CF entry in the doors. A T_F of 10^{-4} is estimated. The 747 is actually less vulnerable than the other aircraft, but the same transfer functions are used to simplify calculations in the following sections and to provide a 747 comparison with the other aircraft.

Section 4.2, Tables 6 and 7, gave the percent time in each operating mode. Those are now combined (including the Lockheed supplied percent time for day and night maintenance) with the transfer function for each operating mode and are listed in Table 13. For example, noting from Table 7 "DAY GATE", APU on, Avionics Door Closed, the Passenger Door is open 95%; and noting from Table 10 "727 CARBON FIBER TRANSFER FUNCTIONS", APU on, Avionics Door Closed, Passenger Door open, the transfer function is 0.7 to the Avionics Bay. The 95% and 0.7 are combined in Table 13 at DAY GATE under Avionics Bay column A1.

Table 13 shows a summary of all operating modes versus aircraft location at the gate or maintenance as a function of transfer functions and percent time.

It can be seen in Table 13 that certain modes/transfer functions dominate; accordingly, it's possible to combine these into a so-called exposure factor.

Exposure factors are drawn from Table 13. For example, take the row for "DAY GATE T_F" and note that 95% of the time the T_F is 0.7 under A1 and 4% of the time 0.7 under E1 adding up to a total of 99% of the time the T_F is 0.7 at day gate. The T_F of 1 for only 1% of the time under B1 turns out to be insignificant when averaging these values. In this manner, Table 14 is established, which sums all operating modes of an aircraft at a particular location. E_{FD} is the Flight Data Exposure Factor and E_{FA} the Avionics Bay.

These exposure factors now provide a modifying factor indicating, on an average, the carbon fiber exposure which may be seen by vulnerable equipment located on the flight deck or in the avionics bay.

Table 13.—Transfer Function (T_F) and Percent Time

	APU ON		AVIONICS BAY ENG. ON		GND. PWR.		AIR CART
	A1	B1	C1	D1	E1	F1	G1
DAY GATE T_F	0.7	1.0	-	-	0.7	-	-
% TIME	95	1	0	0	4	0	0
NIGHT GATE T_F	0.7	-	0.7	-	0.7	1.0	-
% TIME	18	0	2	0	50	30	0
DAY/NIGHT/ MAINTENANCE T_F	0.7	1.0	0.7	1.0	0.7	1.0	0.7
% TIME	7	3	1	1	14	73	1
			FLIGHT DECK				
DAY GATE T_F	0.7	.002	-	-	0.7	-	-
% TIME	95	1	0	0	4	0	0
NIGHT GATE T_F	0.7	-	0.7	-	0.7	0.7	-
% TIME	18	0	2	0	50	30	0
DAY/NIGHT/ MAINTENANCE T_F	0.7	.002	0.7	.002	0.7	0.7	0.7
% TIME	7	3	1	1	14	73	1

A1 - APU ON, Passenger Doors Open
B1 - APU ON, Avionic Doors Open
C1 - Engines ON, Passenger Doors Open
D1 - Engines ON, Avionic Doors Open
E1 - Ground Power, Passenger Doors Open
F1 - Ground Power - Avionic Doors Open
G1 - Air Cart

Table 14.—Exposure Factor (E_F)

	AIRCRAFT LOCATION		
EQUIPMENT LOCATION	DAY GATE	NIGHT GATE	MAINTENANCE
FLIGHT DECK E_{FD}	0.7	0.7	0.7
AVIONICS BAY E_{FA}	0.7	0.8	0.9

6.0 VULNERABLE EQUIPMENT AND PROBABILITY OF REMOVAL

6.1 VULNERABLE EQUIPMENT

The next two sections will describe the identification of vulnerable equipment on the flight deck or in the avionics bay, the statistical probability that the equipment will malfunction because of exposure to CF, the cost of removal and cleaning, and the resulting total probable cost for one aircraft.

At least ninety-five percent of the major electrical/electronic (avionic) equipment on the 707, 727, 737, 747 have been identified and categorized as "sealed" or, if cooling holes (3 millimeter) are present, a "percent open" has been estimated. See Figure 10 and Appendix A. Figure 10 shows the equipment cooling holes or apertures, which may vary widely from approximately 5% to 100% coverage of the case, and the circuit cards and connectors, which may or may not be protected by conformal coat, and the terminals, where a fiber may settle and cause malfunction. Identification and characteristics of each unit were documented on "Component Data Sheets" as shown in the following sample.

Electrical/electronic modules on the flight decks were also identified. Motors, solenoids, transformers, horns, filters, blowers, speakers, and connectors are practically all sealed and are not included. Burndey blocks and relays were not individually identified because it's estimated that their malfunction probabilities from exposure to CF will not significantly impact this study. Flight deck instruments are sealed.

NASA risk analysis contractors measured the vulnerabilities to find "mean exposure" ($\bar{E}$) of an aircraft ATC transponder, VHF communication transceiver, DME Interrogator, VHF-VOR/ILS, Flight Director System, relays, and Burndey Blocks. Carbon fibers of various lengths were used (Reference 3).

From these measured vulnerabilities and also graphite/epoxy fire release data, categories of mean exposures ($\bar{E}$) at which avionic units malfunctioned were specified by NASA for all avionics equipment as follows:

- Category A, open unit - coated boards - unprotected terminals.
  Assign all units an $\bar{E} = 10^8$
- Category B, open unit, uncoated boards, unprotected terminals,
  Assign 1/3 of units an $\bar{E} = 1.5 \times 10^7$
  2/3 $\bar{E} = 1 \times 10^8$
- Category C, open unit, uncoated boards, protected terminals,
  Assign all units an $\bar{E} = 10^8$

All of the vulnerable equipment on the 707, 727, 737, 747 are categorized according to Category A, B, or C with an assigned mean exposure to failure ($\bar{E}$) as shown in the Tables in the next section.

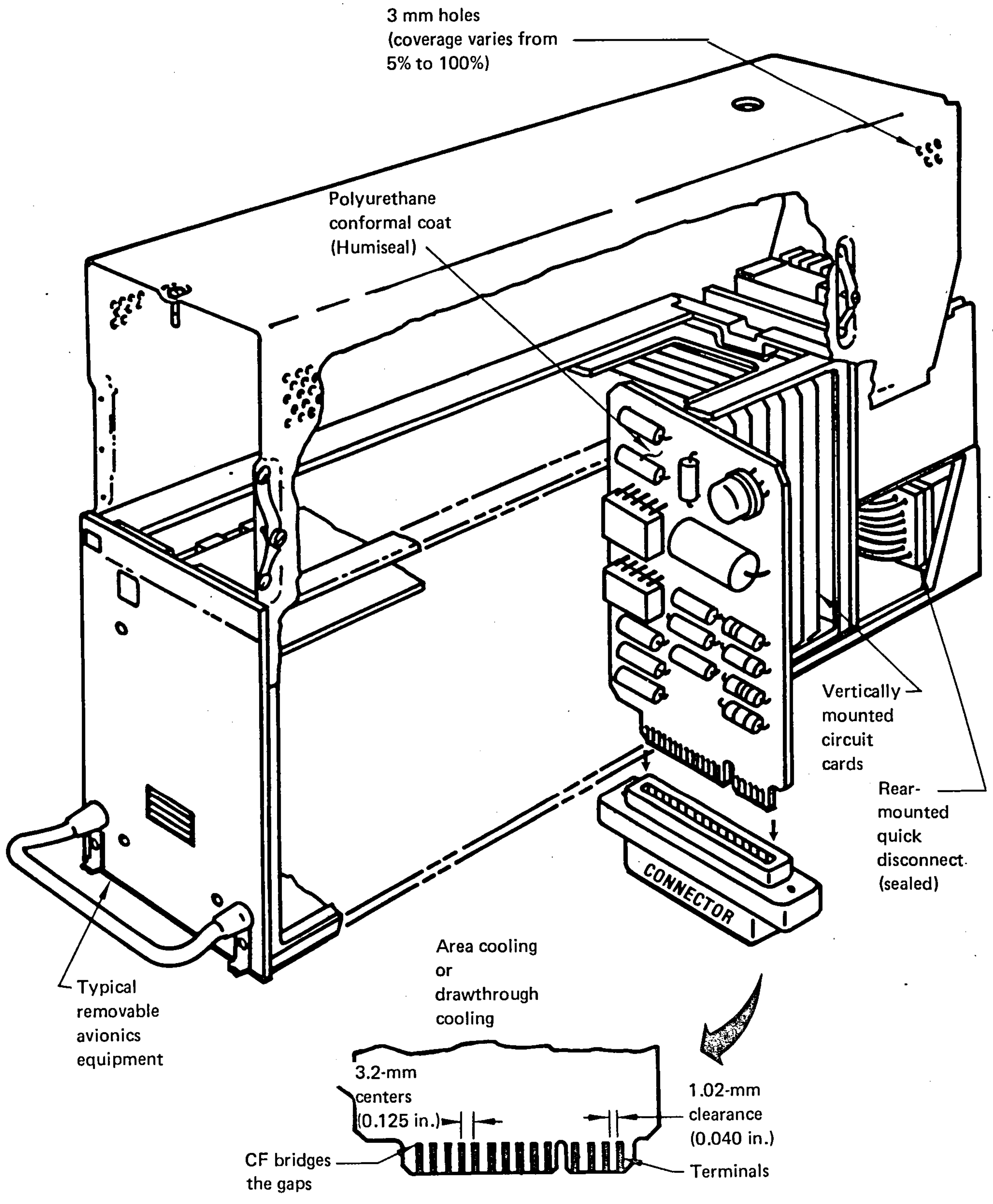

Figure 10.—Equipment Construction and Cooling

COMPONENT DATA SHEET - SAMPLE

1. COMPONENT IDENTIFICATION
   A. NAME
   B. VENDOR
   C. MODEL/P/N
   D. AIRCRAFT MODEL 707 727 737 747
   E. UNITS PER AIRCRAFT 2 2 2 2
   F. SYSTEM Navigation

2. ENCLOSURE
   A. SEALED OPEN X
      NOTE: IF UNIT IS COMPLETELY SEALED DO NOT COMPLETE THE REMAINDER OF THIS FORM.
   B. COOLING - FORCED 747 CONVECTIVE X
      COOLING APERTURES 10-50% .32 cm (1/8")
      AIR FLOW 300, 172 gm/min
      INTERNAL FAN YES NO X COMMENT
      COOLING AIR FILTERED YES NO X TYPE OR
      DESCRIPTION OF FILTER

3. CONSTRUCTION
   A. SUB COMPONENTS
      1. PROTECTED -ALL MOST X SOME NONE X
         (IF MOST, OR SOME, EXPLAIN) May be conformal coat

   B. CARDS/CIRCUITRY
      1. CONFORMAL COATING YES X NO
      2. CARD MOUNTING VERTICAL X HORIZONTAL
      3. CARD SPACING 1.25 cm
      4. ORIENTATION OF BOARD TO AIRFLOW Vertical and Horizontal
      5. HIGH IMPEDANCE CIRCUITS YES X NO
      6. LOGIC CIRCUITS YES X NO DIGITAL X
         ANALOG X
      7. COMMENTS Transformers, Rs, C's, vertical mounted boards approx. 150 terminals on typical board, cards may or may not be coated.

   C. TERMINATIONS
      1. CONNECTORS - PROTECTED X UNPROTECTED
      2. TERMINALS - PROTECTED UNPROTECTED X
      3. TERMINAL SPACING .22 cm to .1 cm
      4. VOLTAGE BETWEEN ADJACENT TERMINALS 115V & logic voltages
      5. COMMENTS

4. VOLTAGES INPUT: 115 VAC
   OUTPUT:
   VOLTAGE RANGE
   PWR SUP 115V, 28V

5. POWER WATTS Unit A 70 to 80, Unit B -48

6. LOCATION - AVIONICS BAY X FLIGHT DECK

7. CRITICALITY - CRITICAL X REDUNDANT X 8. VULNERABILITY
   NON-CRITICAL

6.2 PROBABILITY OF REMOVAL FORMULA

Now that an exposure factor (E_F), and a mean exposure to failure ($\bar{E}$) for equipment have been established, if the aircraft exposure (E) is given, the "probability of equipment removal" can be calculated. Figure 11 shows the concept of aircraft and equipment exposure. For example, an aircraft is assumed to be subjected to CF at the gate, carbon fiber enters the avionics bay or flight deck, resulting in a probability of equipment removal according to the exposure factor and dependent on the mean exposure as follows.

The exponential probability density function formula (random failure) is:

$$P_r\left[UR_{CF}\right] = \left[1 - e^{-E_F\left(\frac{E}{\bar{E}}\right)}\right]$$

where UR_{CF} stands for unscheduled removal because of CF and Pr $[UR_{CF}]$ stands for probability of removal.

The probability of removal is 0.63 when $E = \bar{E}$ (and E_F is one). When the exposure is high, the probability approaches one; when low, the probability approaches zero.

A NASA risk analysis contractor evaluated, for this program, a large number of components and equipment that had malfunctioned and then applied mathematical and statistical "tests" to determine the adherence to or deviations from the above exponential probability distribution (random failure) predictions. The purpose was to determine if the exponential probability distribution applies over the entire range of equipment exposures to carbon fiber, with the emphasis being on extrapolating back down to failure points at very low exposure levels. It was found that certain units/components/equipment did not meet an exponential curve fit. But, most did. It was decided that the random failure prediction would be used to evaluate aircraft avionic equipment because it is conservative and provides for a worst probable case prediction of aircraft susceptibility to CF.

Knowing the probability of removal of the equipment due to exposure to CF, the "dollar cost" to remove the equipment is needed to arrive at the probable dollar loss figure for a single individual aircraft.

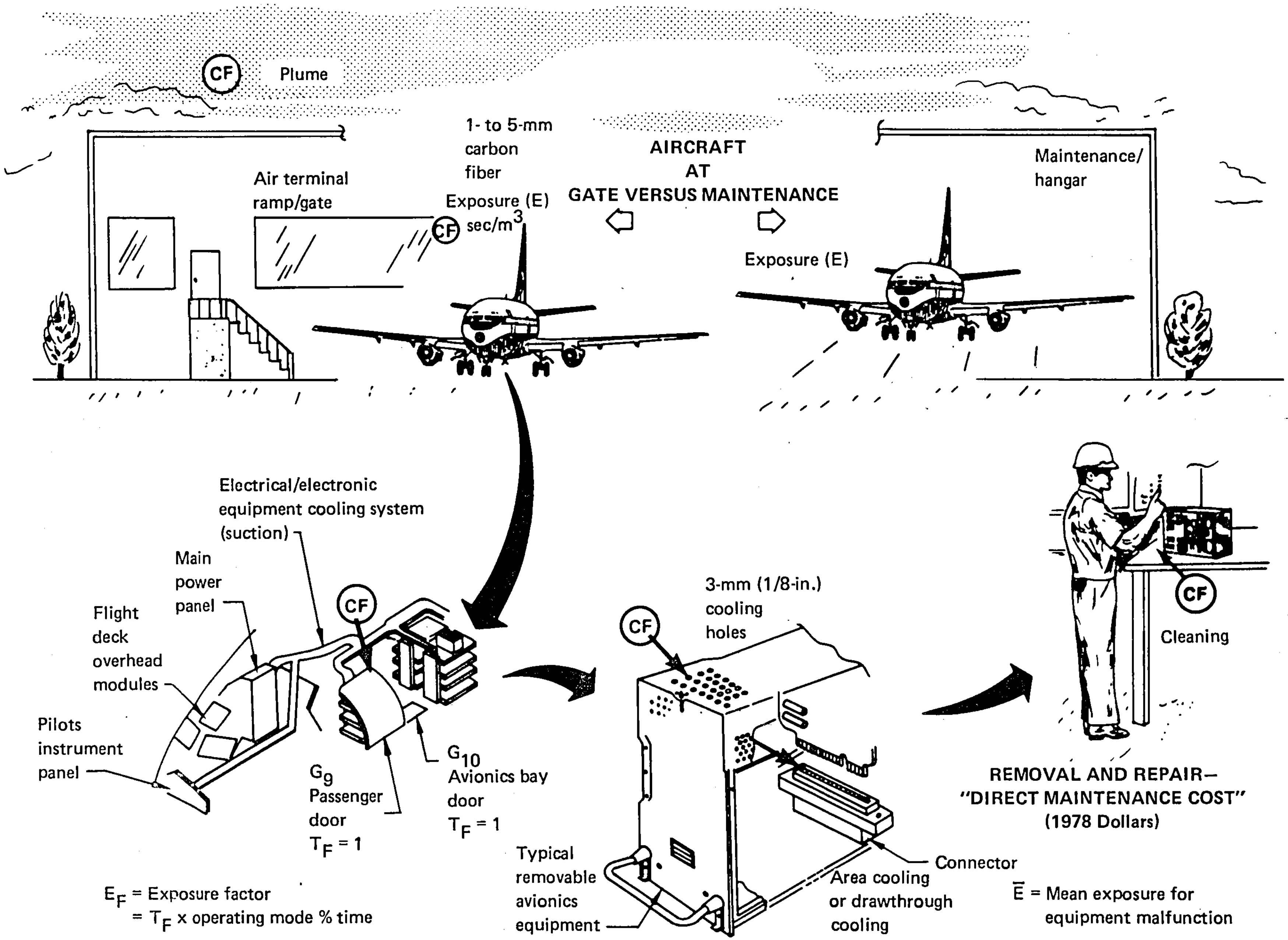

Figure 11.—Cost Assessment

7.0 REMOVAL COST

Removal (and repair) costs are derived from existing Civil Aeronautics Board "Form 41" reports for each individual piece of avionic equipment. Line removal, shop repair, material, overhead, and a "factor for non-reporting" comprise the Direct Maintenance Cost (DMC) in 1977 dollars. The "factor for non-reporting" was removed, labor rates were set at $10.00 per hour, and an overhead of 180% was utilized to arrive at an equivalent 1978 Direct Maintenance Cost (DMC). Aircraft delay at the air terminals (or flight cancellation because of equipment removal) and major overhaul costs are not included. Where data was not available or was obviously not indicative of actual direct maintenance costs, estimates were made; airline cost accounting methods vary widely and influence these figures.

The Direct Maintenance Cost for each vulnerable avionic equipment in an aircraft was evaluated and grouped for equivalent costs (central tendancy), that is, avionics with DMC's of from approximately ten dollars to two-hundred dollars have an average cost of $100.00. In the case of the 737 ("small aircraft"). there were forty-five units with an average of $100. (see Table 15). These units were further separated into those with mean exposure ($\bar{E}$) of 1×10^8 and 1.5×10^7. They were then given EQUIPMENT GROUP numbers, viz., 1 and 2. Group 1 has 38 units and group 2 has 7 units.

The group DMC expected dollar loss is the product of the quantity per aircraft, the average cost, and the "probability of unscheduled removal due to carbon fiber exposure". The sum of the group DMC's is the DMC or "expected dollar loss" per aircraft.

Tables 15, 16, 17 and 18 give the expected dollar loss per 737 aircraft for assumed exposure levels and for the three time and locations of Day Gate, Night Gate, and Maintenance. E_{FD} and E_{FA} are from Table 14. This is the "expected dollar loss" if one aircraft is assumed to be exposed to 3.2×10^7 etc., carbon fiber seconds per cubic meter. Note that the probabilities of removal, $P_r\ (UR_{CF})$, are quite high for the high aircraft exposure level, 3.2×10^7. The maximum expected dollar loss is close to $3000.

The "expected dollar loss" per exposure per aircraft was also calculated for the 707, 727, 737, 747 airplanes for the various locations for an assumed exposure level of 1×10^7. (See Appendix Tables B-1 through B-12). The 737 exposure level (E) is 3.2×10^7 in Table 15 and 1×10^7 in the Appendix Tables. Table 18 summarizes the losses - DMC's - if an aircraft is directly exposed to carbon fibers.

To determine dollar risk, these DMC's must be modified with the "probability of aircraft exposure" per fire accident and annual fire accident rate.

Table 15.—Expected Dollar Loss (1978 dollars), Small Airplanes, Day Gate

$$E = 3.2 \times 10^7$$
$$E_{FD} = 0.7$$
$$E_{FA} = 0.7$$

EQUIP. LOCATION	EQUIP. GROUP	QTY PER A/C	AVG. COST PER UR (1978 $)	$\bar{E}$	$Pr(UR_{CF})$	GROUP CF DMC $/EXPOSURE
AVIONICS BAY	1	38	$100.00	1×10^8	0.201	764.00
AVIONICS BAY	2	7		1.5×10^7	0.775	543.00
AVIONICS BAY	3	6	$450.00	1×10^8	0.201	543.00
AVIONICS BAY	4	2		1.5×10^7	0.775	698.00
FLIGHT DECK	5	1	$300.00	1×10^8	0.201	60.00
FLIGHT DECK	6	18	$ 50.00			181.00
Expected Dollar Loss Per Exposure Per Aircraft Total						$ 2789.00

Table 16.—Expected Dollar Loss (1978 dollars), Small Airplane, Night Gate

$$E = 3.2 \times 10^7$$
$$E_{FD} = 0.7$$
$$E_{FA} = 0.8$$

EQUIP. LOCATION	EQUIP. GROUP	QTY PER A/C	AVG. COST PER UR (1978 $)	$\bar{E}$	$Pr(UR_{CF})$	GROUP CF DMC $/EXPOSURE
AVIONICS BAY	1	38	$ 100.00	1×10^8	0.226	859.00
AVIONICS BAY	2	7		1.5×10^7	0.775	543.00
AVIONICS BAY	3	6	$ 450.00	1×10^8	0.226	610.00
AVIONICS BAY	4	2		1.5×10^7	0.775	698.00
FLIGHT DECK	5	1	$300.00	1×10^8	0.201	60.00
FLIGHT DECK	6	18	$ 50.00			181.00
Expected Dollar Loss Per Exposure Per Aircraft Total						$ 2948.00

Table 17.—Expected Dollar Loss (1978 dollars), Small Airplane, Maintenance

$$E = 3.2 \times 10^7$$
$$E_{FD} = 0.7$$
$$E_{FA} = 0.9$$

EQUIP. LOCATION	EQUIP. GROUP	QTY PER A/C	AVG. COST PER UR (1978 $)	$\bar{E}$	$Pr(UR_{CF})$	GROUP CF DMC $/EXPOSURE
AVIONICS BAY	1	38	$ 100.00	1×10^8	0.250	950.00
AVIONICS BAY	2	7		1.5×10^7	0.853	597.00
AVIONICS BAY	3	6	$ 450.00	1×10^8	0.250	675.00
AVIONICS BAY	4	2		1.5×10^7	0.853	768.00
FLIGHT DECK	5	1	$ 300.00	1×10^8	0.201	60.00
FLIGHT DECK	6	18	$ 50.00			181.00
Expected Dollar Loss Per Exposure Per Aircraft Total						$ 3231.00

Table 18.—Expected Dollar Loss (1978 dollars), Small Airplane, Summary

ASSUMED EXPOSURE LEVEL (E) CF sec/m^3	DAY GATE	NIGHT GATE	MAINTENANCE
3.2×10^3	$ 0.41	$ 0.47	$ 0.52
3.2×10^4	4.1	4.7	5.2
3.2×10^5	41	47	52
3.2×10^6	404	442	489
3.2×10^7	2789	2948	3231

8.0 PROBABILITY OF AIRCRAFT EXPOSURE AND ANNUAL COST

NASA's computer simulation run, developed by A. D. Little (see Appendix C), provides to this study the statistical probability of at least one aircraft exposure per fire accident (0.0004, for example) at an exposure level ($\geq 1 \times 10^7$ CF sec/cubic meter for example). NASA has also provided to this study the aircraft annual accident rate (3.2 fire accidents/year). From this information. it is possible to develop an approximate estimate of the Direct Maintenance Cost on an annual basis for the purpose of obtaining a comparison of the annual DMC due to probability of CF exposure and the annual DMC existing in practice today. This comparison indicates the significance or importance of the CF cost risk.

The existing annual DMC is easily calculated by taking the product of the direct maintenance cost and twice the "unscheduled removal rate" which is given per 1000 hours in CAB Form 41. (At an estimated aircraft utilization rate of 5.7 hours per day, the rate per year, 365 days, works out to approximately 2000 hours, twice the given 1000 hours). Totals are shown in Appendix B, the last line.

The probability of an aircraft being exposed because of a fire accident to a level in excess of 1×10^7 carbon fiber seconds per cubic meter was supplied by NASA and is 0.0004, i.e., there's a chance of 4 in 10,000 that a single aircraft parked at the air terminal will receive an exposure of 10^7 or greater because of a single aircraft accident and fire at some location around the airport.

So, to calculate the carbon fiber DMC, the product of the aircraft exposure probability (0.0004) and the DMC per aircraft gives the DMC per aircraft per accident. See Appendix B.

And, the DMC per aircraft per accident multiplied by the accident rate gives the CF annual DMC per aircraft.

The CF annual DMC and the existing annual DMC comparisons are in Appendix Tables B-1 through B-12. The estimated CF DMC/year is about 0.005% to 0.01% of the existing DMC/year (1978), which obviously indicates an insignificant CF cost risk.

Table 19 summarizes an approximate annual DMC or expected dollar loss per aircraft and shows the very low costs which vary from about a dollar to four dollars at exposures in excess of 1×10^7. These annual costs are calculated from the accident rate of the entire U.S. jet transport fleet.

Table 19.—Annual Expected Dollar Loss Summary for Aircraft Type

707	Day gate	$ 1.10	737	Day gate	$ 1.43
	Night gate	1.21		Night gate	1.59
	Maintenance	1.25		Maintenance	1.75
727	Day gate	1.77	747	Day gate	3.52
	Night gate	1.95		Night gate	3.60
	Maintenance	2.13		Maintenance	3.87

Note: Annual expected dollar loss calculated using:

1. equipment "unscheduled removal" average costs in 1978 dollars
2. equipment "mean exposures" of 1×10^8 or 1.5×10^7
3. aircraft utilization rate of 2,000 hours per year
4. aircraft exposure probability of 0.0004 per aircraft
5. United States fleet accident rate of 3.2 per year
6. Exposure level, $E \geq 1 \times 10^7$

The annual expected dollar loss can also be calculated for the Boeing Commercial Airplane Company 1993 "fleet".

First, a simple frequency distribution table of probability of exposure incidents and aircraft is extracted from the A. D. Little cumulative frequency distribution (Table 11 in Appendix C). The cumulative distribution features of the A. D. Little, Table 11, for both aircraft and exposure parameters must be considered when summing the total aircraft incidents. The probability of all aircraft incidents resulting from exposure in excess of 10^7 CF sec/cubic meter when summed is $12,685 \times 10^{-6}$.

Second, that quantity is multiplied by 3.16, because those aircraft subjected to greater than 10^7 CF sec/cubic meter can be averaged at the geometric mean (3.16) between 10^7 and 10^8. This same procedure is used to calculate the number of aircraft at $E = 3.16 \times 10^6$ and 3.16×10^5 exposure (3.16×10^4 results become negligible). Note that the A. D. Little cumulative frequency distribution table for E greater than 10^6 includes the frequency of incidents for 10^7 and they must be subtracted out. Also note that these aircraft incident probabilities must be "normalized" or scaled by dividing by 10^7 because the aircraft expected dollar loss (Appendix B) has been calculated at the 10^7 exposure levels. In this calculation, the probability density function formula used to calculate aircraft expected dollar loss is assumed to be linear when in fact it is not; the error is considered not significant. The probability of incidents of all models of aircraft subjected to an excess of 10^5 CF sec/cubic meter is $65,201 \times 10^{-6}$ or 0.0652.

Third, this quantity is multiplied by 3.2 fire accidents per year to convert to an annual basis. The result is a probability of 0.209 aircraft incidents per year.

The 1993 "Jet Fleet" percentage of small aircraft has been estimated for this program at 20%. One-half of these are estimated to be Boeing aircraft. Ten percent of 0.209 is 0.0209. From appendix B, the average expected dollar loss of Boeing small aircraft (707, 727, 737) is $1230, which gives a result of $25 annual expected dollar loss for Boeing small aircraft. The 1993 "Jet Fleet" large aircraft percentage is 50%. Boeing large aircraft are estimated at 20%. From Appendix B. the average expected dollar loss is $2860, which gives a result of $120.

The annual expected dollar loss for the Boeing Commercial Airplane Company "fleet" is $145.

9.0 SAFETY

The Boeing Company risk assessment, concerning the possibility of a hazard (from avionic equipment malfunction) to continued aircraft operation after exposure to carbon fiber, is based on evaluations of graphite/epoxy fire characteristics, transport aircraft operational and safety procedures, avionic equipment vulnerabilities to CF, interviews with those experienced in aircraft safety within Boeing, and discussions with the carbon fiber program participants, Douglas and Lockheed.

There are important reasons for believing that there is insignificant hazard to aircraft operation because of accidental graphite/epoxy fires and CF exposure, but first it's necessary to describe certain assumptions made during the cost analyses on this program that allow finite probabilities of equipment malfunction and thus finite costs to be developed. There are three:

One- The cost analysis data (costs for equipment removal after CF exposure) are based on the assumption of extremely high CF exposure (10^7 CF sec/m^3). Based on this assumption, resulting annual costs are finite, but insignificant on a statistical basis. There are no known actual situations where carbon fiber exposure can reach these dense magnitudes (10^7 CF sec/m^3) in an aircraft without causing other overriding problems, such as smoke or soot damage. If it is allowed, however, that these magnitudes can exist, and if one makes a comparison on an annual basis, the estimated CF equipment removal costs or rate compared to actual 1978 removal costs or rate is an insignificant 0.01% or less.

Two- The cost data are based on the assumption of random failures. Tests by NASA's risk analysis subcontractors have caused some avionic equipment to malfunction at very high exposure levels (10^7 CFsec/m^3),but insufficient data exists to verify that the equipment will malfunction at lower exposure levels, that is, the probability of malfunction could be zero for other than the extremely high CF exposures. There is also the condition where multiple fibers are required for malfunction. This dramatically decreases the probability of malfunction at low exposure levels.

Three- The cost data are based on the assumption that the avionic equipment is openly exposed before, during, and after an accidental graphite/epoxy fire occurs and no action is taken to protect, limit, or stop CF from entering an aircraft.

The following important reasons and information developed from this program supports the belief that aircraft safety is not compromised.

What is known is that:

1) Boeing Aircraft are invulnerable to CF when closed up during taxi, takeoff, flight, and landing because of engine and air conditioning filtering. And equally important, a moving aircraft will pass quickly through a CF cloud thus limiting total exposure.

2) Carbon fibers enter through an open passenger, galley, or avionic bay door. CF does not present a substantive, new kind of contaminate.

3) Avionics equipment require extremely high levels of CF exposure (10^7 CFsec/m^3) before malfunction occurs. Burn out or damage does not occur; equipment is restored to normal operation by vacuuming.

4) High levels of carbon fibers are apparent and visible. In a graphite/epoxy fire, heavy soot and smoke accompany the CF. Carbon fibers mat and collect on the equipment or instruments. Such a condition would be improbable and the need for cleanup obvious.

5) Standard pre-flight checkout will verify the operational status of critical avionic equipment that may have been exposed to other than high levels of CF exposure. Avionics subsystems will not simultaneously fail after a successful pre-flight checkout and aircraft flight safety does not depend on single units, but on multiple redundancy.

These facts cause us to believe that aircraft safety is not compromised. In the future, however, avionic equipment cleaning and standard checkout procedures could be implemented after a graphite/epoxy fire at an airport as a precautionary measure to further increase confidence in aircraft safety.

10.0 CONCLUSIONS

This risk study has identified and assessed significant transport aircraft conditions at an air terminal and associated avionics vulnerability to carbon fibers.

Ingestion of carbon fibers into an aircraft may occur when the doors are open, but when a plane is closed during taxi, takeoff, landing, or when parked and the engines or auxiliary power units are operating, carbon fibers are filtered out by the engine and air conditioning system and internal avionics equipment are not exposed. When an aircraft is at an air terminal with the doors open, the plane is usually operating with the auxiliary power unit on during the daytime at the gate with passengers loading, and with ground electrical power on during the nighttime at or away from the gate during ground servicing operations. The specific operating mode, for example, doors open - auxiliary power unit on, establishes the amount of carbon fiber that may enter the aircraft and reach avionic equipment.

Avionic equipment is only vulnerable to malfunction when exposed to extremely dense, visible levels of carbon fibers and can be restored to normal operation by vacuuming.

As determined on this program, avionic equipment probability of malfunction is directly proportional to aircraft probability of exposure, but is an exponential function of direct aircraft (or equipment) exposure. If an aircraft is assumed to be directly exposed to a very high level of carbon fiber (10^7 CFsec/m^3) the probability of an equipment malfunction can be, for certain units, 0.45. There are no known actual situations where carbon fiber exposure can reach these dense magnitudes without causing other overriding problems, such as smoke or soot damage.

If the equipment is removed for cleaning, the removal costs, as calculated for this study, vary from about $50 to $600 in 1978 dollars. Aircraft vulnerable units number from about 60 for the 707 to 175 for the 747 including "flight deck modules"; 40 to 100 without the modules. The removal and cleaning cost, "expected dollar loss", may be $1000 to $3000 after the plane is subjected to an extremely high level of CF, but when adjusting these costs with the aircraft probability of exposure (in 1993) and the annual fire accident rate, the annual cost is reduced to $1 to $4 per year, per aircraft. The estimated CF DMC/year is 0.005% to 0.01% of the existing DMC/year (1978), indicating an insignificant cost risk. The annual expected dollar loss for the Boeing Commercial Airplane Company "fleet" is an insignificant one hundred and forty five dollars.

Although certain assumptions and estimates have been made to simplify calculations in developing the aircraft and equipment vulnerability and removal costs, it's believed they are consistently conservative and that the above figures represent the upper bounds of cost.

In conclusion, the threat to jet transport aircraft is estimated to be so insignificant that the carbon fiber question should not be a factor in deciding whether or not to use graphite/epoxy for aircraft applications.

APPENDIX A
EQUIPMENT LIST

SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
ELECTRICAL POWER						
APU Accessory Unit	Type 1	50			1	
Battery Charger	1	25		1	1	
	2	40				1
Bus Power Control Unit	1	S				2
	2	20				
Bus Protection Panel	1	S		1		
	2	S			1	
DC Voltage Booster	1	50				1
Engine Accessory	1	40			1	
Generator Control Panel	1	S		3		
	2		4			
Generator Control Unit	1	S			2	
	2	S				4
	3	20				
Load Control Unit	1	S		3		
	2					
	3	S				4
Static Inverter	1	100		1	1	1
	2	30				
	3	30				
Transformer/Rectifier (TRU)	1	50	4			
	2	50		3	3	
	3	50				
	4	20				4
Voltage Regulator	1	40		3		
	2	30	4			

S = Sealed Box
F = Fan

SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
NAVIGATION						
ADF	1	20	2	1	1	2
	2	10				
	3	S				
Altitude Alerting Control	1	S	1	1	1	
	2					
ATC Transponder	1	5	2	1	1	2
	2	90				
	3	S				
	4	10				
Compass Coupler	1	15		2		2
DME Iterrogation	1	10-50	2	2F	2F	2
	2					
	3					
	4					
Electronic Buffer Amplifier	1	20				2
Ground Proximity (GPWS) Computer	1	S	1	1	1	1
Inertial Navigation (INS)	1	F (filtered)	2			3
	2					
	3 (not filtered)					
Marker Beacon	1	S	1	1	1	1
	2	2				
	3					
Radio Altimeter	1	30	1	1	1	2
	2	50				
	3	50				
	4	50				
Directional Gyro	1	S	2	2	2	
Vertical Gyro	1	S	2	2	2	

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SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
Vertical Gyro (V/G) Switching Relay	1	S		2	2	
VHF NAV (VOR/ILS)	1	5-40	2	2	2	3
	2	50				
	3	S				
	4	50				
Weather Radar Transceiver	1	F	2	2	2	2
	2	Filter				
	3	Filter				
Weather Radar Indicator	1	10-90	1	1	1	2
	2	S				
<u>COMMUNICATIONS</u>						
Audio Access. Unit	1	15			1	
	2			1		
Cockpit Voice Recorder	1	S	1	1	1	1
	2	S				
Flight Recorder	1	S	1	1	1	
	2	S				
	3	S				
	4	S				
	5	S				
	6	S				
HF Transceiver	1	(Filtered)	2	2	2	2
	2					
	3					
Passenger Address Amplifier	1	S	1	1	1	2
	2	S				
	3	100				
SELCAL	1	S	1	1	1	
	2	S				
	3	S				1

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SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
Tape Music Reproducer	1	30	1	1	1	
	2	30				
VHF Comm Transceiver	1	2	2	1	2	3
	2	40				
	3	S				
	4	S				
<u>AUTOMATIC FLIGHT CONTROL</u>						
Central Instrument Warning Computer	1	25				1
Comparator Warning Monitor	1	10	1	1	1	
AFC Aids Interface	1	10				1
Flight Data Acquisition Unit	1	20			1	1
	2	20				
	3					
Automatic Stabilizer Trim Unit	1	S				1
Autopilot (A/P) Monitor & Logic Unit	1	S				1
Autopilot (A/P) Access. Unit	1	40		1		
	2	40			1	
Autopilot	1		2			
Autopilot Access. Box. No. 1	1	S				1
Autopilot Access. Box No. 1	1	20				1
Automatic Throttle Computer	1	5				1

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SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
Flap/Slat Position	1	20			1	
Flap Load Relief	1	10				1
Gust Response Supression Computer						
- Beta	1	S				1
- MSAS	2	S				1
Mach Trim Coupler	1	5				1
Misc. Solid State Switch	1	40			1	
Overrotation Warning Computer						
Pitch Control Channel (Autopilot)	1	S		1		
	2	S			1	
	3	S				3
Roll Control Channel (Autopilot)	1	S		1		
	2	S			1	
	3	S				3
Stall Warning	1	S				
Rate of Turn Rack	1	15			1	
Signal Summing (Attitude Warning)	Safe Flight					
Stabilizer Trim	1	15				1
Yaw Damper Coupler	1	S			1	
Yaw Damper-Upper	1	S		1		
	2	10				1
Yaw Damper-Lower	1	S			1	
	2	10				1

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SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
<u>FLIGHT DIRECTOR</u>						
Air Data Computer (Central Air Data Computer)	1	10		1	1	
	2	30				
	3	30	2			
	4	10				2
	5			1	1	
Flight Director/ Steering Computer	1	5	1	1	1	
	2					
	3	5	1	1	1	
	4					
Flight Instrument Accessory Unit	1	20			1	
	2	50		1		
Instrument Amplifier (Integrated Instrument System-11S)	1	20	2	2	2	
	2	20				
Leading Edge Flap	1	40				1
Performance Data Computer (New)	1	10	1	1	1	1
Steering Computer/ Flight Director	1	5	2	2	2	
Total Air Temp - TAT/EPR Computer	1	2				1
<u>ICE AND RAIN</u>						
Window and Pitot Static	1	100			1	
Window Heat Control	1	25		4	4	
	2					2

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SYSTEM EQUIPMENT	MANUFACTURER CATEGORIZED:	CONSTRUCTION % OPEN	UNITS PER AIRCRAFT 707	727	737	747
FIRE PROTECTION						
Compartment Fire & Over-heat Detection Unit	1	20-50	1		1	
Fire Detection Unit	1	40	1	1		
AIR CONDITIONING						
Air Conditioning Relay Unit	1	S			1	
Cabin Press Control	1	30		1	1	1
Cabin Temperature Control	1	15			1	
Electronic Turbine Control	1	10				1
Zone and Pack Temperature Controllers	1	15			zone pack	4 3
LANDING GEAR						
Anti Skid Control Module	1	20	1	1	1	1
Auto Brake Accessory or Control	1	50			1	
	2	50		1		
	3	20				1
Landing Gear Accessory	1	80		1	1	
	2	40				1

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F = Fan

APPENDIX B
EXPECTED DOLLAR LOSS

Table B-1.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 707 Airplanes (Aircraft Location: Day Gate)

Equipment location	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\overline{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	24	100	1×10^8	0.0676	162.24
Avionics bay	2	12	100	1.5×10^7	0.3729	447.48
Avionics bay	3	2	300	1×10^8	0.0676	40.56
Avionics bay	4	1	300	1.5×10^7	0.3729	111.87
Flight deck	5	1	150	1×10^8	0.0676	10.14
Flight deck	6	18	70	1×10^8	0.0676	85.18
DMC (expected dollar loss) per exposure per aircraft						$857.47

- Removal probability due to CF per exposure

  $Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F (E/\overline{E})}\right]$

  where E_F = flight deck exposure, $E_{FD} = \underline{0.7}$, or
  avionics bay exposure, $E_{FA} = \underline{0.7}$

  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\ [UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 857 x 0.0004 = $ 0.34 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.34 x 3.2 = $ 1.10 DMC/yr.
- Comparison: $\dfrac{\$\ 1.10\ \text{DMC/yr}}{\$17{,}994\ \text{Existing DMC/yr}} \times 100 = 0.006\ \%$.

Table B-2.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 707 Airplanes (Aircraft Location: Night Gate)

Equipment location	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr[UR_{CF}]$	Group DMC$/exposure
Avionics bay	1	24	100	1×10^8	0.0769	184.56
	2	12		1.5×10^7	0.4134	496.02
	3	2	300	1×10^8	0.0769	46.14
	4	1		1.5×10^7	0.4134	124.02
Flight deck	5	1	150	1×10^8	0.0676	10.14
	6	18	70			85.18
DMC (expected dollar loss) per exposure per aircraft						$946.06

- Removal probability due to CF per exposure

  $Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$

  where E_F = flight deck exposure, E_{FD} = 0.7, or
  avionics bay exposure, E_{FA} = 0.8
  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\ [UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 946 x 0.0004 = $ 0.38 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.38 x 3.2 = $ 1.21 DMC/yr.
- Comparison: $\dfrac{\$\ 1.21\ \text{DMC/yr}}{\$\ 17{,}994\ \text{Existing DMC/yr}} \times 100 = 0.0067\ \%$.

Table B-3.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 707 Airplanes (Aircraft Location: Maintenance)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\overline{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	24	100	1×10^8	0.0861	206.64
	2	12		1.5×10^7	0.4134	496.08
	3	2	300	1×10^8	0.0861	51.66
	4	1		1.5×10^7	0.4134	124.02
Flight deck	5	1	150	1×10^8	0.0676	10.14
	6	18	70			85.18
	DMC (expected dollar loss) per exposure per aircraft					$973.72

- Removal probability due to CF per exposure

$$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\overline{E})}\right]$$

where E_F = flight deck exposure, $E_{FD} = 0.7$, or
avionics bay exposure, $E_{FA} = 0.9$

E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\ [UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 974 x 0.0004 = $ 0.39 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.39 x 3.2 = $1.25 DMC/yr.
- Comparison: $\dfrac{\$\,1.25\ \text{DMC/yr}}{\$17{,}994\ \text{Existing DMC/yr}} \times 100 = 0.0069\ \%$.

Table B-4.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 727 Airplanes (Aircraft Location: Day Gate)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	40	100	1×10^8	0.0676	270.40
	2	11		1.5×10^7	0.3729	410.19
	3	6	450	1×10^8	0.0676	182.52
	4	2		1.5×10^7	0.3729	335.61
Flight deck	5	1	300	1×10^8	0.0676	20.28
	6	48	50			162.24
	DMC (expected dollar loss) per exposure per aircraft					$1,381.24

- Removal probability due to CF per exposure

  $$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$$

  where E_F = flight deck exposure, $E_{FD} = 0.7$, or avionics bay exposure, $E_{FA} = 0.7$

  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\left[UR_{CF}\right]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $1,381 x 0.0004 = $ 0.55 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.55 x 3.2 = $ 1.77 DMC/yr.
- Comparison: $\dfrac{\$\ 1.77\ \text{DMC/yr}}{\$\,20{,}970\ \text{Existing DMC/yr}} \times 100 = 0.0084\ \%$.

Table B-5.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 727 Airplanes (Aircraft Location: Night Gate)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr[UR_{CF}]$	Group DMC$/ exposure
Avionics bay	1	40	100	1×10^8	0.0769	307.60
Avionics bay	2	11		1.5×10^7	0.4134	454.74
Avionics bay	3	6	450	1×10^8	0.0769	207.63
Avionics bay	4	2		1.5×10^7	0.4134	372.06
Flight deck	5	1	300	1×10^8	0.0676	20.28
Flight deck	6	48	50			162.24
DMC (expected dollar loss) per exposure per aircraft						$1,524.55

- Removal probability due to CF per exposure

  $Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F (E/\bar{E})}\right]$

  where E_F = flight deck exposure, $E_{FD} = 0.7$, or
  avionics bay exposure, $E_{FA} = 0.8$

  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr[UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $1,525 x 0.0004 = $ 0.61 DMC/accident.
- DMC/accident x number of accidents/yr = $0.61 x 3.2 = $ 1.95 DMC/yr.
- Comparison: $\dfrac{\$\ 1.95\ \text{DMC/yr}}{\$20{,}970\ \text{Existing DMC/yr}} \times 100 = 0.0093\ \%.$

Table B-6.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 727 Airplanes (Aircraft Location: Maintenance)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr[UR_{CF}]$	Group DMC$/ exposure
Avionics bay	1	40	100	1×10^8	0.0861	344.40
	2	11		1.5×10^7	0.4512	496.32
	3	6	450	1×10^8	0.0861	232.47
	4	2		1.5×10^7	0.4512	406.08
Flight deck	5	1	300	1×10^8	0.0676	20.28
	6	48	50			162.24
	DMC (expected dollar loss) per exposure per aircraft					$1,661.79

- Removal probability due to CF per exposure

  $$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F (E/\bar{E})}\right]$$

  where E_F = flight deck exposure, $E_{FD} = 0.7$, or
  avionics bay exposure, $E_{FA} = 0.9$

  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr[UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 1,662 x 0.0004 = $ 0.66 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.66 x 3.2 = $ 2.13 DMC/yr.
- Comparison: $\dfrac{\$\ 2.13\ \text{DMC/yr}}{\$20{,}970\ \text{Existing DMC/yr}} \times 100 = 0.010\ \%$.

Table B-7.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 737 Airplanes (Aircraft Location: Day Gate)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	38	100	1×10^8	0.0676	256.88
Avionics bay	2	7		1.5×10^7	0.3729	261.03
Avionics bay	3	6	450	1×10^8	0.0676	182.52
Avionics bay	4	2		1.5×10^7	0.3729	335.61
Flight deck	5	1	300	1×10^8	0.0676	20.28
Flight deck	6	18	50			60.84
DMC (expected dollar loss) per exposure per aircraft						$1,117.16

- Removal probability due to CF per exposure

$$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F (E/\bar{E})}\right]$$

where E_F = flight deck exposure, $E_{FD} = 0.7$, or avionics bay exposure, $E_{FA} = 0.7$

E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\ [UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 1,117 x 0.0004 = $ 0.45 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.45 x 3.2 = $ 1.43 DMC/yr.
- Comparison: $\dfrac{\$\ 1.43\ \text{DMC/yr}}{\$18{,}493\ \text{Existing DMC/yr}} \times 100 = 0.0077\ \%$.

Table B-8.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 737 Airplanes (Aircraft Location: Night Gate)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	Pr $[UR_{CF}]$	Group DMC$/ exposure
Avionics bay	1	38	100	1×10^8	0.0769	292.22
Avionics bay	2	7		1.5×10^7	0.4134	289.38
Avionics bay	3	6	450	1×10^8	0.0769	207.63
Avionics bay	4	2		1.5×10^7	0.4134	372.06
Flight deck	5	1	300	1×10^8	0.0676	20.28
Flight deck	6	18	50			60.84
DMC (expected dollar loss) per exposure per aircraft						$1,242.41

- Removal probability due to CF per exposure

  $$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$$

  where E_F = flight deck exposure, $E_{FD} = 0.7$, or avionics bay exposure, $E_{FA} = 0.8$

  $E(\text{exposure}) = 1 \times 10^7$

- Group DMC$/exposure column is obtained by multiplying Pr $[UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 1,242 x 0.0004 = $ 0.50 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.50 x 3.2 = $ 1.59 DMC/yr.
- Comparison: $\dfrac{\$1.59 \text{ DMC/yr}}{\$18{,}493 \text{ Existing DMC/yr}} \times 100 = 0.0086\%$.

Table B-9.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 737 Airplanes (Aircraft Location: Maintenance)

Equipment location	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	38	100	1×10^8	0.0861	327.18
Avionics bay	2	7	100	1.5×10^7	0.4512	315.84
Avionics bay	3	6	450	1×10^8	0.0861	232.47
Avionics bay	4	2	450	1.5×10^7	0.4512	406.08
Flight deck	5	1	300	1×10^8	0.0676	20.28
Flight deck	6	18	50	1×10^8	0.0676	60.85
DMC (expected dollar loss) per exposure per aircraft						$1,362.70

- Removal probability due to CF per exposure

$$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$$

where E_F = flight deck exposure, $E_{FD} = 0.7$, or avionics bay exposure, $E_{FA} = 0.9$

E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying PR $[UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 1,363 x 0.0004 = $ 0.55 DMC/accident.
- DMC/accident x number of accidents/yr = $ 0.55 x 0.32 = $ 1.75 DMC/yr.
- Comparison: $\dfrac{\$1.75 \text{ DMC/yr}}{\$18{,}493 \text{ Existing DMC/yr}} \times 100 = 0.009\ \%$.

Table B-10.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 747 Airplanes (Aircraft Location: Day Gate)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	34	100	1×10^8	0.0676	229.84
	2	6		1.5×10^7	0.3729	223.74
	3	16	300	1×10^8	0.0676	324.48
	4	3		1.5×10^7	0.3729	335.61
Flight deck	5	16	600	1×10^8	0.0676	648.96
	6	73	200			986.96
	DMC (expected dollar loss) per exposure per aircraft					$2,749.59

- Removal probability due to CF per exposure

  $$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$$

  where E_F = flight deck exposure, $E_{FD} = 0.7$, or
  avionics bay exposure, $E_{FA} = 0.7$

  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\left[UR_{CF}\right]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $ 2,750 x 0.0004 = $ 1.10 DMC/accident.
- DMC/accident x number of accidents/yr = $ 1.10 x 3.2 = $ 3.52 DMC/yr.
- Comparison: $\dfrac{\$\ 3.52\ \text{DMC/yr}}{\$69{,}592\ \text{Existing DMC/yr}} \times 100 = 0.0051\ \%$.

Table B-11.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 747 Airplanes (Aircraft Location: Night Gate)

Equipment location	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr[UR_{CF}]$	Group DMC$/ exposure
Avionics bay	1	34	100	1×10^8	0.07688	261.39
	2	6		1.5×10^7	0.4134	248.04
	3	16	300	1×10^8	0.07688	292.14
	4	3		1.5×10^7	0.4134	372.06
Flight deck	5	16	600	1×10^8	0.0676	648.96
	6	73	200			986.96
	DMC (expected dollar loss) per exposure per aircraft					$2,809.55

- Removal probability due to CF per exposure

$$Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$$

where E_F = flight deck exposure, $E_{FD} = 0.7$, or
avionics bay exposure, $E_{FA} = 0.8$

E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr\,[UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $2,810 x 0.0004 = $ 1.12 DMC/accident.
- DMC/accident x number of accidents/yr = $ 1.12 x 3.2 = $ 3.60 DMC/yr.
- Comparison: $\dfrac{\$\ 3.60 \text{ DMC/yr}}{\$69{,}592 \text{ Existing DMC/yr}} \times 100 = 0.0052\ \%$.

Table B-12.—Expected Dollar Loss (1978 Dollars), Avionics Groups For 747 Airplanes (Aircraft Location: Maintenance)

EQUIPMENT LOCATION	Equipment group	Group quantity per aircraft	Group average cost per UR (1978 $)	$\bar{E}$	$Pr\left[UR_{CF}\right]$	Group DMC$/ exposure
Avionics bay	1	34	100	1×10^8	0.0861	292.74
	2	6		1.5×10^7	0.4512	270.72
	3	16	300	1×10^8	0.0861	413.28
	4	3		1.5×10^7	0.4512	406.08
Flight deck	5	16	600	1×10^8	0.0676	648.96
	6	73	200			986.96
	DMC (expected dollar loss) per exposure per aircraft					$3,018.74

- Removal probability due to CF per exposure

  $Pr\left[UR_{CF}\right] = \left[1 - e^{-E_F\,(E/\bar{E})}\right]$

  where E_F = flight deck exposure, $E_{FD} = 0.7$, or
  avionics bay exposure, $E_{FA} = 0.9$

  E(exposure) = 1×10^7

- Group DMC$/exposure column is obtained by multiplying $Pr[UR_{CF}]$ by quantity per aircraft and by group average cost per UR (1978 $).
- DMC/E/aircraft x Pr [E] = $3,019 x 0.0004 = $ 1.21 DMC/accident.
- DMC/accident x number of accidents/yr = $ 1.21 x 3.2 = $ 3.87 DMC/yr.
- Comparison: $\dfrac{\$\ 3.87\ \text{DMC/yr}}{\$69{,}592\ \text{Existing DMC/yr}} \times 100 = 0.0056\ \%$.

APPENDIX C

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PROBABILITIES OF EXPOSURE OF JET AIRCRAFT AT MAJOR U.S. AIRPORTS

I. INTRODUCTION

The purpose of this memorandum is to summarize an analysis performed of potential carbon fiber exposures at major U.S. airports. The results of this analysis will be utilized in conjunction with a safety analysis and a risk analysis of electronic components within U.S. aircraft. The analysis was performed by Monte Carlo simulation using Arthur D. Little's carbon fiber dispersion and risk analysis model.

The major finding of the analysis is that probabilities of exposure that can reasonably affect the electronic systems of U.S. jet aircraft are extremely small. The probability of a fire accident resulting in an exposure of 10^3 fs/m^3 at either the gate or maintenance area of a major airport is 2.2%. The corresponding probabilities of exposures in excess of 10^4, 10^5, 10^6, and 10^7 are 1.4%, .7%, .3%, and .04% respectively. The probabilities of these exposures affecting given numbers of aircraft, and breakdowns by day and night and by maintenance and gate areas are presented in Section III.

The conclusions were based on certain assumptions and simplifications. The major assumption was that all of the aircraft in either the gate or maintenance area would experience the identical exposure in any fire accident. Another way of looking at this is that we assumed that aircraft were for the purposes of the model located at the same point. Exposure probabilities were computed analyzing exposures at one maintenance point and two gate points. A second major assumption was that at any given point during the day or night the number of aircraft on the ground would be equal to the average for the day or night period. Thus, the probabilities were computed by determining exposure probabilities at given locations and then assuming that all the aircraft in the gate or maintenance area were located at these locations. These assumptions lower the probability of any aircraft experiencing a given exposure but increase the probability that all planes experience the given exposure.

It was also assumed within the context of the ADL dispersion model that the direction and velocity of the wind would not change in the course of the dispersion. This assumption has the practical affect of causing a thin cloud to disperse in a given direction without any variation or changes in direction. In actuality, a fire or explosion on or near the airport may be subject to some variation in speed and direction. However, even allowing for error due to these assumptions, it is clear that significant exposures at airport locations are highly unlikely.

There are two major reasons why the exposure probabilities at airport locations are extremely small. First, under the most likely set of release conditions a plume release does not result in substantial exposures at locations close to the source of the plume. Cases analyzed by Arthur D. Little previously show that distance to the beginning of the 10^3 contour is usually several thousand meters. If, as in the case of most aircraft accidents, the location of the fire is close to the airport then the plume cloud will not result in high exposures at the airport. The second reason is that even in the case of an explosive release, the width of the cloud is quite narrow at locations close to the source of the accident. Thus, it is very unlikely that an explosive release will affect a particular location. This event will only occur if the wind direction is precisely in the direction of that location. Our model simplifies the true situation by locating all of the aircraft at a small number of points. Actual probabilities of any aircraft being covered by a given exposure might be higher than estimated. To compensate for this, we assume that all the aircraft are exposed if any are.

The results presented in this memorandum are aggregated over all sizes of aircraft because there is a great deal of correlation in the exposure probabilities for small, medium and large aircraft. It is not very meaningful to present probabilities of exposure for small, medium, and large aircraft taken separately.

II. METHODOLOGY

The analysis was performed in the following steps:

- For each of 9 major airports we computer coded the location of the maintenance area and two central gate points
- We executed the Arthur D. Little carbon fiber dispersion and risk analysis model to compute the probability of exposure at various levels at the particular locations.
- For each airport, we evaluated the probability of a given number of aircraft being exposed during the day and night operations by assuming that the average number of planes on the ground are all located at a single point representative of the sample points used in the program.

- We computed the national probability of exposure for a given number of planes by mixing the individual airport probabilities according to the number of estimated operations of aircraft carrying carbon fibers. As noted, the assumption that all of the aircraft are located at a given point overestimates the probability that any plane will be covered by a given exposure. On the other hand, it underestimates the probability that all of either the gate or maintenance aircraft can experience a given exposure.

The gate and maintenance area coordinates were determined from airport maps and were computed in relation to the centroid of the airports runways. The precise distances were extremely important in the analysis and hence the assumptions of accident locations in the risk analysis model should be reviewed. For each airport, a probability distribution for the given runway was input and accidents taking place off the runway were located according to a model based on historical data. Takeoff and landing accidents taking place on or near the airport were assumed to take place at the center of the appropriate runway. Static and taxi accidents were assumed to take place near the gate area and were therefore located between the two gate locations utilized for exposure sampling.

The dispersion model is the modified model being utilized by Arthur D. Little in its national risk assessment being performed for NASA. This model is the same as the model presented in a previous report except for the following modifications:

- Time of burn, percent of fuel burned and percent of carbon fiber structures consumed are based on a probabilistic distribution constructed from a data base of 92 fire and explosion accidents compiled by Lockheed, Douglas, and Boeing. Correlations among these variables were implemented and the distribution for percent of carbon fiber structures consumed is consistent with a structural damage model developed by Lockheed.

- Carbon fiber usage on aircraft is consistent with the production forecasts up to an including 1993 by the three airframe manufacturers. Fleets of aircraft that use carbon fibers are assumed to be split equally among the airframe manufacturers appropriate for each size of aircraft.

- Maximum percentage of carbon fibers released is assumed to be 1% and 4% for plume and explosive releases respectively.

- Maximum fuel loads are consistent with the types of aircraft that are dominating the 1993 fleet mix.

- Probability of explosive release is conservatively estimated to be 15%. This is consistent with the 92 fire and explosion accidents compiled by Lockheed, Douglas, and Boeing. This estimate is conservative in a sense that not all of these explosions represent burns followed by an explosion. The probability of an explosive release is higher than 15% for take-off accidents taking place on or near the runway and slightly lower than 15% for landing accidents.

In the next step of the analysis, probability distributions were estimated using the model for each of the nine airports at the maintenance and the gate areas conditional on there being a fire accident. These conditional distributions are presented in Table 1.

In the next step of the analysis the conditional distributions represented in Table 1 were combined with the statistics of the number of planes at each airport during the day and night in the gate and maintenance area to produce a distribution of number of planes being exposed to a given exposure.

In the final step of the analysis we assumed that every fire accident will occur at one of the nine airports. By making this assumption we can use the nine airports to project a national risk profile. In order to perform the final step, it was necessary to compute the conditional probability that an accident occurred at a particular one of these nine airports given that it occurred at one of the nine airports. The equation utilized in computing these probabilities is

Prob C_i is proportional to(estimated 1993 operations) x

(weather factor) x (percent CF)

Derivation of the weather factor and the estimated 1993 operation are presented in the Arthur D. Little report for Phase 1. The percentage of CF represents the percentage of operations at a given airport in 1993 that will involve aircraft utilizing CF. These percentages were estimated utilizing the airframer estimates for percent of 1993 fleets carrying CF and projections of operations mixes by aircraft type at each given airport. Factors utilized in the computation and the conditional probability of each major city are presented in Table 2.

To estimate the conditional probability that an accident occurs during the day and night operations, we examined operations statistics at two airports and accident times for the 92 accidents cited previously. For Boston, the percentage of operations taking place during the night hours is 6% and for Washington, D.C. and Atlanta the percentages are 3.5% and

22% respectively. The percentage of night accidents in the data base is 25%. (These were the only data available). We, therefore, equate the nighttime probability of an accident at Washington to be 3.5% x the probability of an accident. For Boston, and for other cities that we judged to be mainly daytime airports we estimated the probability of an accident occurring during the nighttime hours as 6% x the probability of an accident. These cities included Boston, LaGuardia, Philadelphia, and St. Louis. For the other airports, Atlanta, Chicago, Kennedy, and Miami, which we judged to be active 24 hour airports we estimated that the probability of an accident taking place during the night hours is 25% x the probability of an accident. This estimate is consistent with the statistics from the 92-accident data base and the operations data from Atlanta. We used the 25% figure rather than 22% since there seems to be some evidence that night operations involve slightly more risk.

The conditional probability that an accident takes place at a given airport along with the day-night probabilities were utilized in constructing the overall distributions. These are presented in the next section.

III. RESULTS

The aggregate distributions for the number of aircraft experiencing a given exposure value are presented in Table 3 through 6. These tables represent the four conditions of interest which are day and night for gate and maintenance. Tables 7 through 10 present the aggregated and maintenance distributions and Table 11 represents the overall distributions. As noted previously, the conditional probability of aircraft being exposed to moderate exposure values is very low.

To convert these probabilities to annual values, each of the probabilities should be multiplied by 3.2 to represent the number of accidents occurring in a year. Thus, for example, the conditional probability of 10 or more planes being exposed to an exposure of 10^5 or greater is .69%. The annual probability of exposing 10 planes or greater to 10^5 or greater exposure is 3.2 x .69% or 2.2%. Table 12 through 20 are the analog of Tables 3 through 11 on an annual basis.

In order to estimate the size of the aircraft involved Table 21 presents the average fleet mix for aircraft exposed for each of the different situations.

TABLE 1

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: JFK

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability that Gate Exposure Exceeds Value
10^3	.014	.0125
10^4	.008	.0080
10^5	.004	.0030
10^6	.0015	.0015
10^7	0	0

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: Chicago

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability that Gate Exposure Exceeds Value
10^3	.0165	.0105
10^4	.0085	.0080
10^5	.0040	.0045
10^6	.0005	.0030
10^7		.005

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: Miami

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Excceds Value
10^3	.022	.0118
10^4	.0115	.0063
10^5	.005	.0033
10^6	.0025	.0008
10^7	.0005	.0003

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: Atlanta

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Exceeds Value
10^3	.016	.0118
10^4	.0105	.0078
10^5	.007	.0033
10^6	.003	.0008
10^7		.0003

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: LaGuardia

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Exceeds Value
10^3	.0075	.0103
10^4	.0045	.0073
10^5	.0030	.0048
10^6	.0015	.0023
10^7		.0008

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: DC National

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Excceds Value
10^3	.017	.014
10^4	.011	.0095
10^5	.010	.0070
10^6	.0055	.0040
10^7		.0005

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: Boston

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Exceeds Value
10^3	.006	.0009
10^4	.004	.0006
10^5	.002	.0005
10^6		.0001
10^7		.000025

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE AREAS FOR NINE AIRPORTS

Airport: Philadelphia

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Exceeds Value
10^3	.0165	.0105
10^4	.0090	.0065
10^5	.0035	.0060
10^6	.0005	.0030
10^7		.0010

TABLE 1 (CONTINUED)

CONDITIONAL EXPOSURE DISTRIBUTIONS AT GATE AND MAINTENANCE
AREAS FOR NINE AIRPORTS

Airport: St. Louis

Exposure (fs/m^3)	Probability That Maintenance Exposure Exceeds Value	Probability That Gate Exposure Exceeds Value
10^3	.0105	.0075
10^4	.008	.0045
10^5	.0055	.0015
10^6	.0015	.0005
10^7		

TABLE 2

COMPUTATION OF THE CONDITIONAL PROBABILITY OF A CITY

	Estimated 1993 Op	Weather Factor	% CF	Probability
Atlanta	433,434	1.09	.54	.159
Boston	171,897	1.06	.63	.072
Chicago	599,339	1.04	.72	.280
Kennedy	289,275	1.05	.81	.154
LaGuardia	213,724	1.05	.61	.085
Miami	249,330	.65	.78	.079
Philadelphia	138,520	1.04	.60	.054
St. Louis	165,764	.99	.50	.051
Washington	189,295	.87	.64	.066

TABLE 3

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Gate Day

Number of Planes n	Exposure E (fs/m^3) 10^3	10^4	10^5	10^6	10^7
2	.008500	.005760	.003000	.001450	.000312
4	.008500	.005760	.003000	.001450	.000312
7	.008500	.005760	.003000	.001450	.000312
10	.008500	.005760	.003000	.001450	.000312
11	.007900	.005360	.002800	.001350	.000262
12	.007900	.005360	.002800	.001350	.000262
13	.007900	.005360	.002800	.001350	.000262
14	.007900	.005360	.002800	.001350	.000262
16	.007900	.005360	.002800	.001350	.000262
18	.007000	.004760	.002300	.001150	.000232
19	.006600	.004500	.002200	.001120	.000230
20	.005800	.003900	.001800	.000920	.000170
21	.005800	.003900	.001800	.000920	.000170
24	.005800	.003900	.001800	.000920	.000170
25	.005800	.003900	.001800	.000920	.000170
28	.005600	.003900	.001800	.000920	.000170
31	.005100	.003500	.001600	.000870	.000150
37	.005100	.003500	.001600	.000870	.000150
38	.003700	.002600	.001200	.000770	.000110
54	.003700	.002600	.001200	.000770	.000110
55	.001500	.000900	.000300	.000170	.000000

TABLE 4

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Gate Night

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.002034	.001426	.000681	.000337	.000065
4	.002034	.001426	.000681	.000337	.000065
7	.002034	.001426	.000681	.000337	.000065
10	.002014	.001412	.000676	.000335	.000065
11	.001984	.001392	.000662	.000327	.000065
12	.001984	.001392	.000662	.000327	.000065
13	.001954	.001372	.000642	.000318	.000062
14	.001954	.001372	.000642	.000318	.000062
16	.001904	.001332	.000622	.000306	.000056
18	.001404	.001032	.000502	.000246	.000058
19	.001400	.001030	.000500	.000246	.000058
20	.001400	.001030	.000500	.000246	.000058
21	.001400	.001030	.000500	.000246	.000058
24	.001400	.001030	.000500	.000246	.000058
25	.000700	.000430	.000200	.000046	.000018
28	.000700	.000430	.000200	.000046	.000018
31	.000700	.000430	.000200	.000046	.000018
37	.000200	.000130	.000070	.000016	.000006
38	.000200	.000130	.000070	.000016	.000006
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 5

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Maintenance Day

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.009100	.005160	.002800	.000920	.000030
4	.008200	.004500	.002400	.000850	.000030
7	.008200	.004500	.002400	.000850	.000030
10	.006900	.003900	.002100	.000700	.000030
11	.005300	.003000	.001600	.000500	.000000
12	.001900	.001200	.000800	.000400	.000000
13	.001900	.001200	.000800	.000400	.000000
14	.000000	.000000	.000000	.000000	.000000
16	.000000	.000000	.000000	.000000	.000000
18	.000000	.000000	.000000	.000000	.000000
19	.000000	.000000	.000000	.000000	.000000
20	.000000	.000000	.000000	.000000	.000000
21	.000000	.000000	.000000	.000000	.000000
24	.000000	.000000	.000000	.000000	.000000
25	.000000	.000000	.000000	.000000	.000000
28	.000000	.000000	.000000	.000000	.000000
31	.000000	.000000	.000000	.000000	.000000
37	.000000	.000000	.000000	.000000	.000000
38	.000000	.000000	.000000	.000000	.000000
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 6

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Maintenance Night

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.002270	.001240	.000615	.000163	.000010
4	.002270	.001240	.000615	.000163	.000010
7	.002240	.001220	.000595	.000158	.000010
10	.002240	.001220	.000595	.000158	.000010
11	.002240	.001220	.000595	.000158	.000010
12	.002240	.001220	.000595	.000158	.000010
13	.002240	.001220	.000595	.000158	.000010
14	.002240	.001220	.000595	.000158	.000010
16	.001740	.000920	.000485	.000108	.000000
18	.001740	.000920	.000485	.000108	.000000
19	.001740	.000920	.000485	.000108	.000000
20	.001740	.000920	.000485	.000108	.000000
21	.001740	.000920	.000485	.000108	.000000
24	.001700	.000900	.000470	.000100	.000000
25	.001700	.000900	.000470	.000100	.000000
28	.000500	.000300	.000170	.000060	.000000
31	.000500	.000300	.000170	.000060	.000000
37	.000000	.000000	.000000	.000000	.000000
38	.000000	.000000	.000000	.000000	.000000
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 7

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Day

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.017600	.010920	.005800	.002370	.000342
4	.016700	.010260	.005400	.002300	.000342
7	.016700	.010260	.005400	.002300	.000342
10	.015400	.009660	.005100	.002150	.000312
11	.013200	.008360	.004400	.001850	.000262
12	.009800	.006560	.003600	.001750	.000262
13	.009800	.006560	.003600	.001750	.000262
14	.007900	.005360	.002800	.001350	.000262
16	.007900	.005360	.002800	.001350	.000262
18	.007000	.004760	.002300	.001150	.000232
19	.006600	.004500	.002200	.001120	.000230
20	.005800	.003900	.001800	.000920	.000170
21	.005800	.003900	.001800	.000920	.000170
24	.005800	.003900	.001800	.000920	.000170
25	.005800	.003900	.001800	.000920	.000170
28	.005800	.003900	.001800	.000920	.000170
31	.005100	.003500	.001600	.000870	.000150
37	.005100	.003500	.001600	.000870	.000150
38	.003700	.002600	.001200	.000770	.000110
54	.003700	.002600	.001200	.000770	.000110
55	.001500	.000900	.000300	.000170	.000000

TABLE 8

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Night

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.004304	.002666	.001296	.000500	.000075
4	.004304	.002666	.001296	.000500	.000075
7	.004274	.002646	.001276	.000495	.000075
10	.004254	.002632	.001271	.000493	.000075
11	.004224	.002612	.001257	.000485	.000075
12	.004224	.002612	.001257	.000485	.000075
13	.004194	.002592	.001237	.000476	.000072
14	.004194	.002592	.001237	.000476	.000072
16	.003644	.002252	.001107	.000414	.000058
18	.003144	.001952	.000987	.000354	.000058
19	.003140	.001950	.000985	.000354	.000058
20	.003140	.001950	.000985	.000354	.000058
21	.003140	.001950	.000985	.000354	.000056
24	.003100	.001930	.000970	.000346	.000056
25	.002400	.001330	.000670	.000146	.000016
28	.001200	.000730	.000370	.000106	.000018
31	.001200	.000730	.000370	.000106	.000016
37	.000200	.000130	.000070	.000016	.000006
38	.000200	.000130	.000070	.000016	.000006
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 9

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Gate

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.010534	.007186	.003681	.001787	.000377
4	.010534	.007186	.003681	.001787	.000377
7	.010534	.007186	.003681	.001787	.000377
10	.010514	.007172	.003676	.001785	.000377
11	.009884	.006752	.003462	.001677	.000327
12	.009884	.006752	.003462	.001677	.000327
13	.009854	.006732	.003442	.001668	.000324
14	.009854	.006732	.003442	.001668	.000324
16	.009804	.006692	.003422	.001656	.000320
18	.008404	.005792	.002802	.001396	.000290
19	.008000	.005530	.002700	.001366	.000286
20	.007200	.004930	.002300	.001166	.000226
21	.007200	.004930	.002300	.001166	.000226
24	.007200	.004930	.002300	.001166	.000228
25	.006500	.004330	.002000	.000966	.000188
28	.006500	.004330	.002000	.000966	.000188
31	.005800	.003930	.001800	.000916	.000168
37	.005300	.003630	.001670	.000886	.000156
38	.003900	.002730	.001270	.000786	.000116
54	.003700	.002600	.001200	.000770	.000110
55	.001500	.000900	.000300	.000170	.000000

TABLE 10

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Maintenance

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.011370	.006400	.003415	.001083	.000040
4	.010470	.005740	.003015	.001013	.000040
7	.010440	.005720	.002995	.001008	.000040
10	.009140	.005120	.002695	.000858	.000010
11	.007540	.004220	.002195	.000658	.000010
12	.004140	.002420	.001395	.000558	.000010
13	.004140	.002420	.001395	.000558	.000010
14	.002240	.001220	.000595	.000158	.000010
16	.001740	.000920	.000485	.000108	.000000
18	.001740	.000920	.000485	.000108	.000000
19	.001740	.000920	.000485	.000108	.000000
20	.001740	.000920	.000485	.000108	.000000
21	.001740	.000920	.000485	.000108	.000000
24	.001700	.000900	.000470	.000100	.000000
25	.001700	.000900	.000470	.000100	.000000
28	.000500	.000300	.000170	.000060	.000000
31	.000500	.000300	.000170	.000060	.000000
37	.000000	.000000	.000000	.000000	.000000
38	.000000	.000000	.000000	.000000	.000000
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 11

PROBABILITY CONDITIONAL ON AN ACCIDENT THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Overall

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.022400	.014010	.007355	.003018	.000417
4	.021500	.013350	.006955	.002948	.000417
7	.021470	.013330	.006935	.002943	.000417
10	.020170	.012630	.006635	.002793	.000367
11	.017970	.011330	.005935	.002493	.000337
12	.014570	.009530	.005135	.002393	.000337
13	.014540	.009510	.005115	.002384	.000334
14	.012640	.008310	.004315	.001984	.000334
16	.012140	.008010	.004185	.001924	.000320
18	.010740	.007110	.003585	.001624	.000290
19	.010340	.006850	.003485	.001594	.000288
20	.009540	.006250	.003085	.001394	.000226
21	.008940	.005850	.002785	.001274	.000228
24	.008900	.005830	.002770	.001266	.000228
25	.008200	.005230	.002470	.001066	.000188
28	.007000	.004630	.002170	.001026	.000188
31	.006300	.004230	.001970	.000976	.000168
37	.005300	.003630	.001670	.000886	.000156
38	.003900	.002730	.001270	.000786	.000116
54	.003700	.002600	.001200	.000770	.000110
55	.001500	.000900	.000300	.000170	.000000

TABLE 12

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED
TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Gate Day

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.027200	.018432	.009600	.004640	.000998
4	.027200	.018432	.009600	.004640	.000998
7	.027200	.018432	.009600	.004640	.000998
10	.027200	.018432	.009600	.004640	.000998
11	.025280	.017152	.008960	.004320	.000838
12	.025280	.017152	.008960	.004320	.000838
13	.025280	.017152	.008960	.004320	.000838
14	.025280	.017152	.008960	.004320	.000838
16	.025280	.017152	.008960	.004320	.000838
18	.022400	.015232	.007360	.003680	.000742
19	.021120	.014400	.007040	.003584	.000736
20	.018560	.012480	.005760	.002944	.000544
21	.018560	.012480	.005760	.002944	.000544
24	.018560	.012480	.005760	.002944	.000544
25	.018560	.012480	.005760	.002944	.000544
28	.018560	.012480	.005760	.002944	.000544
31	.016320	.011200	.005120	.002784	.000480
37	.016320	.011200	.005120	.002784	.000480
38	.011840	.008320	.003840	.002464	.000352
54	.011840	.008320	.003840	.002464	.000352
55	.004800	.002880	.000960	.000544	.000000

TABLE 13

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

<u>Case: Aggregate Gate Night</u>

Number of Planes n	Exposure E (fs/m^3): 10^3	10^4	10^5	10^6	10^7
2	.006309	.004563	.002179	.001080	.000209
4	.006309	.004563	.002179	.001080	.000209
7	.006309	.004563	.002179	.001080	.000209
10	.006445	.004518	.002163	.001073	.000209
11	.006349	.004454	.002118	.001048	.000206
12	.006349	.004454	.002118	.001048	.000206
13	.006253	.004390	.002054	.001019	.000199
14	.006253	.004390	.002054	.001019	.000199
16	.006093	.004262	.001990	.000980	.000186
18	.004493	.003302	.001606	.000788	.000186
19	.004480	.003296	.001600	.000787	.000186
20	.004480	.003296	.001600	.000787	.000186
21	.004480	.003296	.001600	.000787	.000186
24	.004480	.003296	.001600	.000787	.000186
25	.002240	.001376	.000640	.000147	.000058
28	.002240	.001376	.000640	.000147	.000058
31	.002240	.001376	.000640	.000147	.000058
37	.000640	.000416	.000224	.000051	.000019
38	.000640	.000416	.000224	.000051	.000019
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 14

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED
TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Maintenance Day

Number of Planes n	Exposure (fs/m^3) 10^3	10^4	10^5	10^6	10^7
2	.029120	.016512	.008960	.002944	.000096
4	.026240	.014400	.007680	.002720	.000096
7	.026240	.014400	.007680	.002720	.000096
10	.022080	.012480	.006720	.002240	.000000
11	.016960	.009600	.005120	.001600	.000000
12	.006080	.003840	.002560	.001280	.000000
13	.006080	.003840	.002560	.001280	.000000
14	.000000	.000000	.000000	.000000	.000000
16	.000000	.000000	.000000	.000000	.000000
18	.000000	.000000	.000000	.000000	.000000
19	.000000	.000000	.000000	.000000	.000000
20	.000000	.000000	.000000	.000000	.000000
21	.000000	.000000	.000000	.000000	.000000
24	.000000	.000000	.000000	.000000	.000000
25	.000000	.000000	.000000	.000000	.000000
28	.000000	.000000	.000000	.000000	.000000
31	.000000	.000000	.000000	.000000	.000000
37	.000000	.000000	.000000	.000000	.000000
38	.000000	.000000	.000000	.000000	.000000
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 15

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED
TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Maintenance Night

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.007264	.003968	.001968	.000522	.000032
4	.007264	.003968	.001968	.000522	.000032
7	.007168	.003904	.001904	.000506	.000032
10	.007168	.003904	.001904	.000506	.000032
11	.007168	.003904	.001904	.000506	.000032
12	.007168	.003904	.001904	.000506	.000032
13	.007168	.003904	.001904	.000506	.000032
14	.007168	.003904	.001904	.000506	.000032
16	.005568	.002944	.001552	.000346	.000000
18	.005568	.002944	.001552	.000346	.000000
19	.005568	.002944	.001552	.000346	.000000
20	.005568	.002944	.001552	.000346	.000000
21	.005568	.002944	.001552	.000346	.000000
24	.005440	.002880	.001504	.000320	.000000
25	.005440	.002880	.001504	.000320	.000000
28	.001600	.000960	.000544	.000192	.000000
31	.001600	.000960	.000544	.000192	.000000
37	.000000	.000000	.000000	.000000	.000000
38	.000000	.000000	.000000	.000000	.000000
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 16

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED
TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Day

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.056320	.034944	.018560	.007584	.001094
4	.053440	.032832	.017280	.007360	.001094
7	.053440	.032832	.017280	.007360	.001094
10	.049280	.030912	.016320	.006880	.000998
11	.042240	.026752	.014080	.005920	.000838
12	.031360	.020992	.011520	.005600	.000838
13	.031360	.020992	.011520	.005600	.000638
14	.025280	.017152	.008960	.004320	.000836
16	.025280	.017152	.008960	.004320	.000638
18	.022400	.015232	.007360	.003680	.000742
19	.021120	.014400	.007040	.003584	.000736
20	.018560	.012480	.005760	.002944	.000544
21	.018560	.012480	.005760	.002944	.000544
24	.018560	.012480	.005760	.002944	.000544
25	.018560	.012480	.005760	.002944	.000544
28	.018560	.012480	.005760	.002944	.000544
31	.016320	.011200	.005120	.002784	.000480
37	.016320	.011200	.005120	.002784	.000480
38	.011840	.008320	.003840	.002464	.000352
54	.011840	.008320	.003840	.002464	.000352
55	.004800	.002880	.000960	.000544	.000000

TABLE 17

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

<u>Case: Aggregate Night</u>

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.013773	.008531	.004147	.001601	.000241
4	.013773	.008531	.004147	.001601	.000241
7	.013677	.008467	.004083	.001585	.000241
10	.013613	.008422	.004067	.001579	.000241
11	.013517	.008358	.004022	.001553	.000240
12	.013517	.008358	.004022	.001553	.000240
13	.013421	.008294	.003958	.001524	.000231
14	.013421	.008294	.003958	.001524	.000231
16	.011661	.007206	.003542	.001326	.000186
18	.010061	.006246	.003158	.001134	.000186
19	.010048	.006240	.003152	.001133	.000186
20	.010048	.006240	.003152	.001133	.000186
21	.010048	.006240	.003152	.001133	.000186
24	.009920	.006176	.003104	.001107	.000186
25	.007680	.004256	.002144	.000467	.000058
28	.003840	.002336	.001184	.000339	.000058
31	.003840	.002336	.001184	.000339	.000058
37	.000640	.000416	.000224	.000051	.000019
38	.000640	.000416	.000224	.000051	.000019
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 18

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED
TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Gate

Exposure E (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.033709	.022995	.011779	.005720	.001207
4	.033709	.022995	.011779	.005720	.001207
7	.033709	.022995	.011779	.005720	.001207
10	.033645	.022950	.011763	.005713	.001207
11	.031629	.021606	.011078	.005366	.001046
12	.031629	.021606	.011078	.005368	.001046
13	.031533	.021542	.011014	.005339	.001037
14	.031533	.021542	.011014	.005339	.001037
16	.031373	.021414	.010950	.005300	.001024
18	.026893	.018534	.008966	.004468	.000928
19	.025600	.017696	.008640	.004371	.000922
20	.023040	.015776	.007360	.003731	.000730
21	.023040	.015776	.007360	.003731	.000730
24	.023040	.015776	.007360	.003731	.000730
25	.020800	.013856	.006400	.003091	.000602
28	.020800	.013856	.006400	.003091	.000602
31	.018560	.012576	.005760	.002931	.000536
37	.016960	.011616	.005344	.002835	.000499
38	.012480	.008736	.004064	.002515	.000371
54	.011840	.008320	.003840	.002464	.000352
55	.004800	.002880	.000960	.000544	.000000

TABLE 19

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Maintenance

Number of Planes n	Exposure E (fs/m^3) 10^3	10^4	10^5	10^6	10^7
2	.036364	.020480	.010928	.003466	.000128
4	.033504	.018368	.009648	.003242	.000128
7	.033408	.018304	.009584	.003226	.000128
10	.029248	.016384	.008624	.002746	.000032
11	.024128	.013504	.007024	.002106	.000032
12	.013248	.007744	.004464	.001786	.000032
13	.013248	.007744	.004464	.001786	.000032
14	.007168	.003904	.001904	.000506	.000032
16	.005568	.002944	.001552	.000346	.000000
18	.005568	.002944	.001552	.000346	.000000
19	.005568	.002944	.001552	.000346	.000000
20	.005568	.002944	.001552	.000346	.000000
21	.005568	.002944	.001552	.000346	.000000
24	.005440	.002880	.001504	.000320	.000000
25	.005440	.002880	.001504	.000320	.000000
28	.001600	.000960	.000544	.000192	.000000
31	.001600	.000960	.000544	.000192	.000000
37	.000000	.000000	.000000	.000000	.000000
38	.000000	.000000	.000000	.000000	.000000
54	.000000	.000000	.000000	.000000	.000000
55	.000000	.000000	.000000	.000000	.000000

TABLE 20

ANNUAL PROBABILITY THAT n OR MORE PLANES ARE EXPOSED
TO AN EXPOSURE OF E OR LARGER

Case: Aggregate Overall

Exposure (fs/m^3)

Number of Planes n	10^3	10^4	10^5	10^6	10^7
2	.071680	.044832	.023536	.009658	.001334
4	.068800	.042720	.022256	.009434	.001334
7	.068704	.042656	.022192	.009418	.001334
10	.064544	.040416	.021232	.008938	.001238
11	.057504	.036256	.018992	.007978	.001078
12	.046624	.030496	.016432	.007658	.001078
13	.046528	.030432	.016368	.007629	.001069
14	.040448	.026592	.013808	.006349	.001069
16	.038848	.025632	.013392	.006157	.001024
18	.034368	.022752	.011472	.005197	.000928
19	.033068	.021920	.011152	.005101	.000922
20	.030528	.020000	.009872	.004461	.000730
21	.028608	.018720	.008912	.004077	.000730
24	.028480	.018656	.008864	.004051	.000730
25	.026240	.016736	.007904	.003411	.000602
28	.022400	.014816	.006944	.003283	.000602
31	.020160	.013536	.006304	.003123	.000538
37	.016960	.011616	.005344	.002835	.000499
38	.012480	.008736	.004064	.002515	.000371
54	.011840	.008320	.003840	.002464	.000352
55	.004800	.002880	.000960	.000544	.000000

TABLE 21

AVERAGE FLEET MIX FOR AIRCRAFT EXPOSED IN ACCIDENTS

	% Small	% Medium	% Large
Maintenance Day	79.2	2.1	18.7
Maintenance Night	70.5	8.2	21.3
Gate Day	79.2	5.5	15.3
Gate Night	75.2	6.6	18.2
Maintenance Overall	75.5	4.7	19.8
Gate Overall	78.7	5.7	15.6
Day Overall	79.2	5.0	15.8
Night Overall	72.9	7.4	19.7
Overall	78.0	5.4	16.6

REFERENCES

1. Assessment of Carbon Fiber Electrical Effects, NASA CP-2119, NASA Scientific and Technical Information Office, 1980.

2. The Transfer of Carbon Fiber Through a Commercial Aircraft Water Separator and Air Cleaner, CR159183, Bionetics Corporation, J. A. Meyers, November 1979.

3. The Vulnerability of Commercial Aircraft Avionics to Carbon Fibers, CR159213, Bionetics Corporation, J. A. Meyers, Seymour Salmirs, April 1980.

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15. Supplementary Notes

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16. Abstract

This report presents results of a program to investigate the possible effects of free carbon fibers on aircraft avionic equipment operation, removal costs, and safety. This aircraft risk assessment was established to identify and quantify possible carbon fiber flow paths, flow rates, and transfer functions into the Boeing 707, 727, 737, 747 aircraft and potentially vulnerable equipment therein. Probabilities of equipment removal and probabilities of aircraft exposure to carbon fiber were derived from data supplied by NASA.

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